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THE DEVELOPMENT OF GUIDELINES FOR A STATISTICALLY BASED PROCESS--ETC(U)

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The Development of Guidelines for a Statistically Based Process Control System for the Earthwork Phase of Earth Dam Construction Projects

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Final report--March 1980

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A thesis submitted to The Pennsylvania State University in partial fulfillment of the requirements for the degreee of Master of Science in Civil Engineering.

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The Pennsylvania State University

The Graduate School

Department of Civil Engineering

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The Development of Guidelines for a Statistically Based Process Control System for the Earthwork Phase of Earth Dam Construction Projects

A Thesis in

Civil Engineering

by

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William D. Roudabush

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ABSTRACT

This thesis provides a contractor involved in earthen dam construction with the appropriate tools and techniques needed to develop and implement a statistically based process control system for the impervious zone (or core). Initial research consisted of an extensive literature search to obtain background material related to compaction of embankments and obtaining the plans, specifications, and test data from the Corps of Engineers dam site used as an example in the thesis. Personal interviews were conducted with contractor and Corps personnel at the dam site directed toward gaining insight into the current practices involved in Corps dam construction projects and their comments concerning feasibility of a statistically based process control system. The practical situation observed and implemented on the Corps dam for embankment compaction of earthen dams was meshed with the theory of statistically based process control. A set of guidelines was developed for a contractor to use to set up a statistically based process control system for compaction of the impervious zone of earthen dams. The collected data were then used to demonstrate the statistically based process control techniques involved in analyzing test data for the impervious zone of an earthen dam.

Through the use of a statistical process control system, the contractor could predict his future performance, receive advanced warning of problems in his process that could affect his acceptance results, and identify and eliminate those problems before they do affect his acceptance results.

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CHAPTER 1

INTRODUCTION

Compaction is the process of mechanically densifying a soil. Densification is accomplished by pressing the soil particles together into a closer state of contact, with air being expelled from the soil mass in the process. Compaction, as used here, implies dynamic compaction or densification by the application of moving loads to the soil mass.

Certain advantages which accompany the compaction of soils have made the process of compaction a standard procedure in the construction of earth structures such as embankments. No single construction process which can be applied to natural soils produces so marked a change in their physical properties at so low a cost as compaction. Principal soil properties which are affected by compaction include deformation, shearing resistance, movement of water, and volume change.

Advantages Gained from Compaction

One of the principal advantages which results from the compaction of soils used in embankments is that it reduces to a minimum the settlement which might be caused by the consolidation of the soil within the body of the embankment. This is true because compaction and consolidation both bring about a closer arrangement of the soil particles. Densification by compaction will reduce settlement of the embankment, but this does not necessarily mean that the embankment will

be free from settlement, since its weight may cause consolidation of compressible soil layers which may form the embankment foundation.

Increasing density by compaction usually increases shearing resistance. This effect is highly desirable in that it may make possible the use of steeper side slopes for an embankment than would otherwise be possible. In addition to density, shearing resistance depends on water content and several other factors. For the same density, the highest strengths are frequently obtained by the use of greater compactive efforts and with water contents somewhat below optimum moisture content. Large scale experiments conducted by the United States Army Corps of Engineers indicated that the unconfined compressive strength of clayey sand could be doubled by compaction, within the range of practical field compaction procedures (39).

When soil particles are forced together by compaction, both the amount of voids contained in the soil mass and the size of the individual void spaces are reduced. This change in voids has an obvious effect upon the movement of water through the soil. One effect is to reduce the permeability, thus reducing the seepage of water. Somewhat similarly, if the compaction is accomplished with proper moisture control, the movement of capillary water is minimized, thus reducing the tendency of the soil to take up water and suffer later reductions in shearing resistance.

Moisture-Density Relationships

Nearly all soils exhibit a similar relationship between moisture content and dry density when subjected to a given compactive effort. For each soil, there is developed a maximum dry density at an optimum

moisture content for the compactive effort used. The maximum moisture content at which the maximum dry density is obtained is the moisture content at which the soil has become sufficiently workable under the given amount of compactive effort to cause the soil particles to become so closely packed as to expel most of the air. For most soils (except cohesionless sands), when the moisture content is less than optimum, the soil is more difficult to compact. Beyond optimum, most soils are not as dense under a given compactive effort. Beyond optimum and for the given compactive effort, the air content of most soils remains essentially the same, even though the moisture content is increased.

For each compactive effort which is used in compacting a given soil, there is a corresponding optimum moisture content and maximum dry density. If the compactive effort is increased, the maximum dry density is increased and the optimum moisture content is decreased. If the same soil is compacted under different compactive efforts, it is possible to develop a relationship between density and compactive effort for that soil. This information is of particular interest to the engineer preparing specifications for the compaction and to the inspector who must interpret the results of field density tests taken during compaction. In the field, the compactive effort is a function of the type of roller, weight of the roller, and the number of passes for a given lift thickness and width of the area of the soil which is being rolled. Increasing the weight of the roller or the number of passes generally increases the compactive effort. Other factors that may be of consequence include lift thickness, contact pressure, and in the case of sheepsfoot rollers, the size and length of the tamping feet.

Need for Research

Webster's dictionary defines quality control as "a system for maintaining desired standards in production or in a product, especially by inspecting samples of the product." With the advent and proven applicability of statistically based performance specifications in the highway construction industry, the need for research to define an effective process control system for a contractor on dam embankment construction has surfaced. Statistical process control appears to be a powerful tool which may be used to assist in meeting the embankment specifications. Some contractors may be familiar with process control techniques that are used in the highway construction industry; therefore, they could probably easily adapt the techniques to dam construction. Since the majority probably do not have this familiarity, this research was performed with the objective of providing practical guidelines which could be used as a part of a process control system.

Major use of, and need for, statistically based process control systems for the earthwork phase of earth dam construction is in large part limited to the Corps of Engineers and the Bureau of Reclamation due to the federal involvement in the vast majority of dam construction in the United States. Although the federal government has influenced quality control development, the procedures and policies have come from separate departments and are therefore fragmented and differing.

The trend in quality control is away from the traditional intuitive approaches toward the more organized and scientific approaches. A standardized procedural guideline for the development of a statistically based process control system for the earthwork phase of earth dam construction projects would provide the contractor having a traditional

or semi-developed program with the background information he needs to create his own system.

Research Procedures and Objectives

It is the writer's opinion that a contractor would benefit from the implementation of a statistically based process control system for the compaction of earthen dams. This thesis will provide a contractor involved in earthen dam construction with the appropriate tools and techniques he would need in order to develop a statistically based process control system. Process control theory will be provided for the contractor who may be unfamiliar with statistical quality control applications.

Existing earthen dam construction practices and data presented in this thesis were obtained from a United States Army Corps of Engineers dam site which will be identified in this thesis as Dam A. The writer obtained the plans, specifications, and test data during a site visit. Subsequent telephone conversations and mail transactions were used to supplement this information.

The development of a process control system would normally involve an implementation and revision process to determine its effectiveness and/or feasibility. The data collected at Dam A was historical in nature and, therefore, did not enable this process to be accomplished. Consequently, only the first phase involving the initial development of the system was carried out. Accordingly, the following three objectives have been established.

The first objective of this thesis is to mesh the theory of statistically based process control with the practical situation

observed and implemented on Dam A for embankment compaction of earthen dams.

The second objective is to develop a set of guidelines a contractor could use in order to set up a statistically based process control system for compaction of the impervious zone of earthen dams.

The third objective is to demonstrate the statistically based process control techniques involved in analyzing test data for the impervious zone of an earthen dam. Data used in the analysis were obtained by the writer from historical records of the impervious zone on Dam A.

Organization of Thesis

Chapter 2 contains a literature review of some soil compaction factors, soil characteristics related to earthen dam construction, and statistical control of compaction. Chapter 3 is a discussion of the concepts of process control in terms of the control chart technique. Chapter 4 describes Dam A operations, testing procedures and facilities, and currently used compaction controls and control procedures. A general procedure for developing a process control system for the impervious zone is described. Chapter 5 deals with the analysis of data which was obtained on the Dam A project for the impervious zone in the form of process control charts and tabulation techniques. Chapter 6 contains general observations, conclusions, and the future research needs which were established as a result of this research. Appendix A consists of an abbreviated form of the embankment specification being used on Dam A. Appendix B provides an abbreviated form of

the Contractor Quality Control plan as currently used on Corp projects. Appendix C presents the impervious zone data used for the analysis phase presented in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

A literature review was conducted in order to determine the importance and use of soil compaction factors related to embankment compaction, as well as to determine the sources of variability that exist in the operation. Previous research related to Statistical Quality Control procedures for compaction, and typical U. S. Army Corps of Engineers embankment specifications used on Corps dam projects were also examined. The present methods by which the Corps specifies and conducts acceptance testing for embankment compaction was also investigated. The first two areas of review will be discussed in this chapter; the last two will be discussed in Appendix A and Chapter 4, respectively.

Soil Compaction Factors

Compaction is the process by which a mass of soil consisting of solid soil particles, air, and water is reduced in volume by the momentary application of loads, such as rolling, tamping, or vibration. Compaction involves an expulsion of air without significantly changing the amount of water in the soil mass. Thus, the moisture content of the soil, which is defined as the ratio of weight of water to the weight of dry soil particles, is normally the same for loose, uncompacted soil as for the same soil after compaction to a denser state. Since the amount of air is reduced without change in the amount of water in the soil mass, the degree of saturation (ratio of volume of water to combined volume of air and water) increases. In most soils,

however, the expulsion of all the air cannot be achieved by compaction; hence, 100% saturation does not occur. When used as a construction material, the significant properties of soil are its shear strength, compressibility, and permeability. Compaction of the soil generally increases its shear strength, decreases its compressibility, and decreases its permeability.

When considering the compaction of soils, two broad classifications of soils can be considered separately: (1) cohesive soils, and (2) cohesionless (noncohesive) soils. Cohesive soils are those which contain sufficient quantities of silt or clay to render the soil mass impermeable when properly compacted. Such soils are all varieties of clays, silts, and silty or clayey sands or gravels which include those that fall into the Unified Soils Classification Groups CY, CL, MH, ML, SC, SM, GC, GM, and boundary groups of any two of these. On the other hand, cohesionless soils are the relatively clean sands and gravels which remain pervious even when well compacted. Soil Groups SW, SP, GW, and GP, and boundary groups of any of these two represent such soils (16).

Behavior of Cohesive Soils Under Compaction. An important characteristic of cohesive soils is the fact that compaction improves their engineering properties of shear strength and compressibility. For each compaction procedure, it has been found that there is an "optimum" moisture content which results in the greatest dry density or state of compactness. At every other moisture content, both dry and wet of "optimum," the resulting dry density is less than the maximum. Figure 1 shows two moisture density curves (Proctor curves)

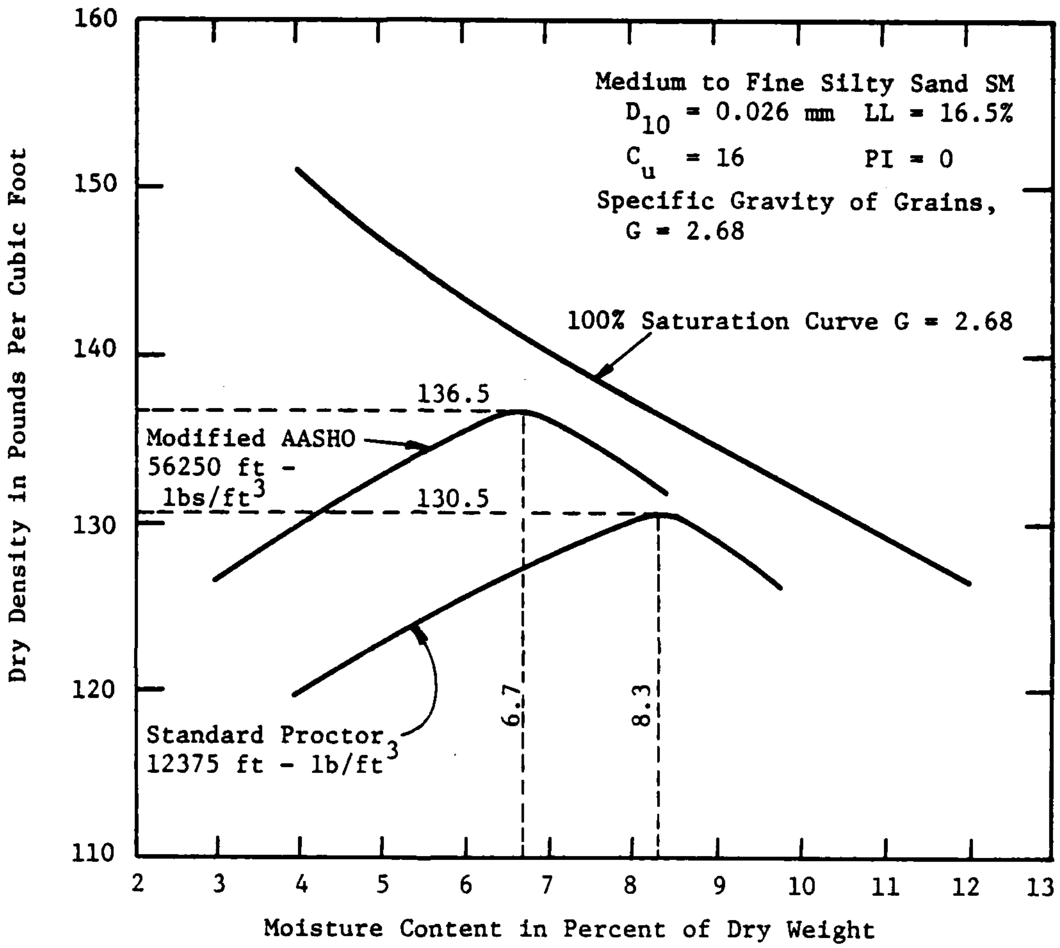


Figure 1. Moisture-Density Curves of a Cohesive Soil for Different Compactive Efforts (39)

for different amounts of compactive effort on the same soil. Note that a different Proctor curve is obtained for each compactive effort, but each curve has the characteristic peaked shape (6).

Each cohesive soil has its own characteristic moisture-density curve for a given compactive effort. The compactive effort used to obtain the curves for the three types of soil in Figure 2, for instance, has been found to approximate the compaction achieved in the field by 12 passes of a 20-ton dual-drum sheepsfoot roller on 8- to 9-inch loose layers of cohesive soils.

Even though most cohesive soils used in compacted fills have their own characteristic compaction curves, it has been found that in some certain soils, such as those formed by the weathering of rocks in place (residual soils), have moisture-density curves for a given compacted effort which are not unique. The compaction curves change depending on the moisture content of the soil at the start of the particular compaction test (39). The process that results in the peaked compaction curve is quite complex as a result of the combined effect of physical and physiochemical factors.

Soil is porous--that is, it contains interconnected void spaces between the grains, thus permitting the flow of fluids through the soil mass. The volume of voids in a soil mass is less important from the standpoint of permeability than the size of the pores. The amount of voids in a soil mass may be expressed as its porosity (the volume of voids per unit volume of soil mass, usually expressed as a percentage). The void ratio is the volume of voids per unit volume of solid soil particles, usually expressed as a decimal.

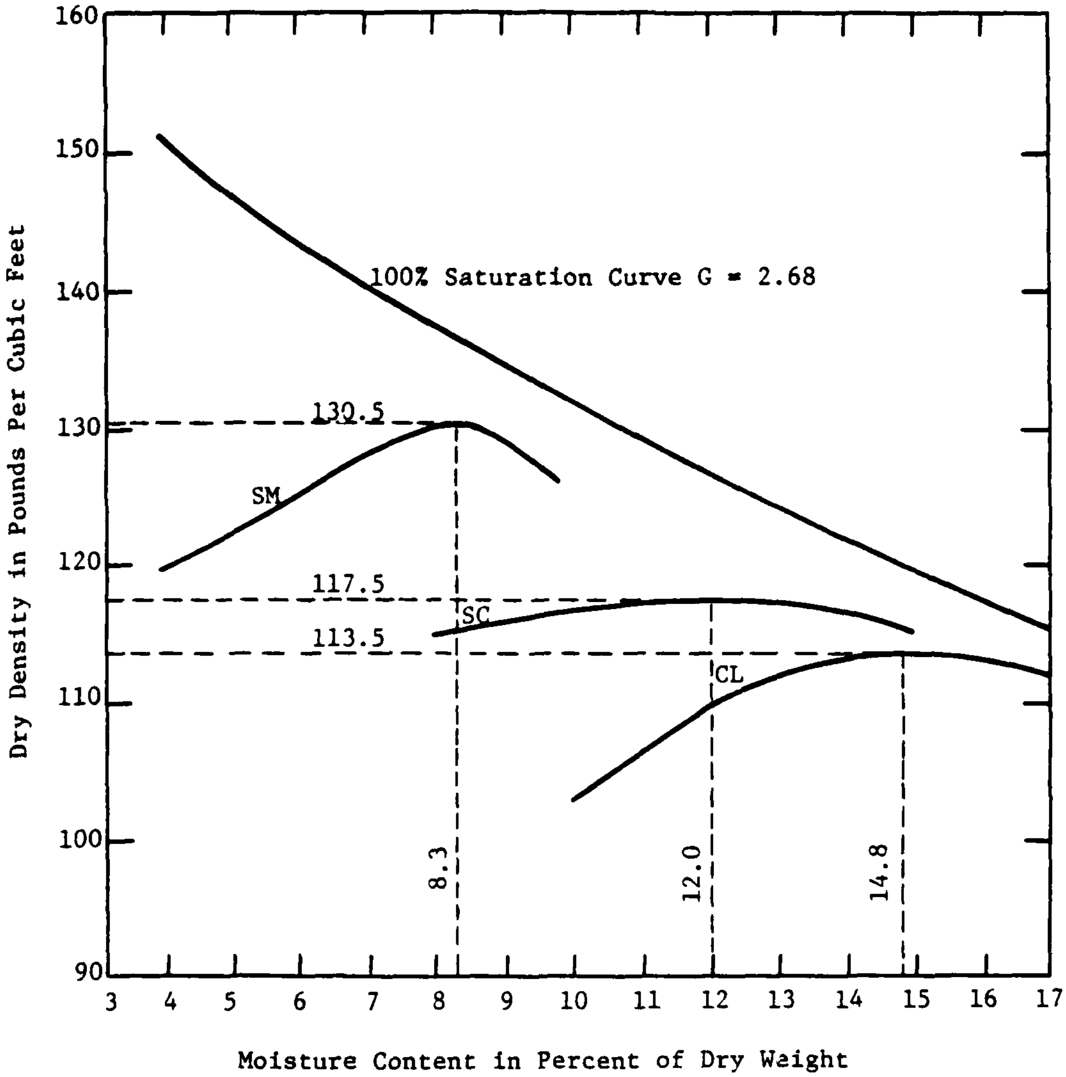


Figure 2. Standard Proctor Curves for Three Soils with the Same Specific Gravity (30)

Compacting the soil by the same method but with a higher moisture content causes a greater rearrangement of the variously sized soil particles due to the increased lubrication furnished by the additional water. The result is a soil of greater density, but one which is not as firm.

This effect continues as the amount of water in the soil increases until the point at which the moisture content, combined with a small amount of contained air that the compaction process cannot remove, becomes just sufficient to fill the voids when the compaction process is completed. The soil then has the greatest density (least voids) that this method of compaction can obtain.

A still higher moisture content limits the compaction to a point at which the voids equals the volume of the contained air and water, resulting in a compacted soil with more voids, less density, and increased plasticity (softness). This effect continues with the addition of more water until the soil becomes too soft to sustain compacting equipment.

The shape of the compaction curve can also be explained by the concepts of capillary pressure and pore-air pressure. Dry soils are difficult to compact because of the appreciable friction force caused by the high curvature of the menisci which resists the compactive effort. Air, however, is expelled quickly because the air voids are relatively large. When the soil is compacted at an increased water content, the menisci flatten and cannot resist compactive effort as well as do the drier soils; hence, density increases until the maximum point is reached. The decrease of dry density with increasing water content beyond the optimum can be attributed to water "diluting" the

soil particles, i.e., the number of soil particles in a unit volume of soil mass decreases.

For compaction at relatively low moisture contents, increases in moisture increase the degree of saturation resulting in higher pore pressures (air and water). This weakens the soil by reducing the effective stresses between the particles. The soil particles slide over one another until sufficiently large lateral stresses and horizontal shearing stresses with the layer previously compacted have developed to give the soil the requisite effective stress. As the soil is subjected to further compactive effort, the effective stresses increase due to three factors: increases in the residual lateral total stresses, the increasing negative residual pore-water pressure, and the fact that the shear-induced increases in pore-water pressure become progressively smaller. Small increases in dry density continue to occur as additional compactive effort is applied, since local concentration of shear stresses will cause localized densification.

The same line of reasoning applies as the water content is increased further, except that the decreasing air permeability may result in the development of significant pore-air pressures. Eventually, enough water may be added to the soil so that air channels become discontinuous, and the air is trapped. When the air voids become completely discontinuous, the air permeability of the soil drops to zero and no further densification is possible. The soil has reached the so-called "optimum moisture content."

<u>Shear Strength of Compacted Cohesive Soils</u>. The shear strength of a given compacted cohesive soil depends on the density and the

moisture content at the time of shear. The pore-water pressures developed while the soil is being subjected to shear are of great importance in determining the strength of such soils. Pore pressures produced by volume changes coincident with the shearing process act to reduce the apparent strength of a compacted cohesive soil. Compaction of a soil at water contents slightly less than optimum often results in a net increase in strength because the slight reduction in friction value (which accompanies the reduction in density) is more than compensated for by the comparatively large reduction in pore pressure which is thereby obtained.

During construction of a rolled fill, the objective is for each layer of the soil to be identical and to be compacted at the same moisture content and to the same density. Immediately following compaction, the soil is assumed to be virtually unstressed externally. However, capillary pressures (negative pore-water pressures) exist in the soil. These stresses are accompanied by normal effective stresses which are equal in all directions within the soil layer. As construction proceeds, the load of superimposed layers of fill simultaneously applies normal and shear stresses to the soil below, causing it to change in volume, and inducing pore-air pressures and changes in capillary pressures.

Compressibility of Compacted Cohesive Soils. Cohesive soils vary in compressibility depending on the amount and character of fines and the amount and gradation of the coarse particles they contain. The compressibility of a compacted cohesive soil depends on its density and moisture content at the time of loading. A compacted cohesive soil

which has been placed at too dry a moisture content will probably undergo collapse when saturated under load. The collapse mechanism is controlled by three factors: (1) a potentially unstable structure, such as a flocculent type associated with soils compacted dry of optimum, or with loess soils; (2) a high applied stress which further increases the instability; and (3) a high suction which provides the structure with a temporary rigidity and whose removal on wetting leads to collapse. The absence of any one of these three factors removes the possibility of significant collapse (39).

Behavior of Cohesionless Soils Under Compaction. Because these soils are relatively pervious when compacted, they are not significantly affected by their water content during the compaction process. Consequently, the peaked curve relationship between dry density and water content (Proctor curve) that was just noted for cohesive soils is ill-defined or nonexistent for clean sands and gravels. For a given compactive effort on the latter soils, the dry density obtained is high when the soil is completely dry and high when the soil is completely saturated. Somewhat lower densities occur when the soil has intermediate amounts of water. The explanation for this involves the phenomenon of bulking in sands where small capillary stresses in the partially saturated soil tend to resist the compactive effort. This bulking phenomenon is not present in completely dry sand and disappears when the moist sand is saturated.

Where the Proctor curve concept is not applicable, the normally used compaction criterion is relative density. This term, which was introduced by Terzaghi (36), is defined as:

$$D_r = \frac{e_{max} - e}{e_{max} - e_{min}} ,$$

where

e_{max} = void ratio of the soil in its loosest state,

e = void ratio of the soil being tested,

e_{min} = void ratio of the soil in its densest state, and

D_r = relative density, usually expressed as percent.

Terzaghi (36), as translated by Casagrande in 1960, considered it possible to judge whether a sand is deposited in a loose or dense state by evaluating its relative density and its compactability. Terzaghi defined compactability of soils as:

$$F = \frac{e_{max} - e_{min}}{e_{min}} .$$

In well-graded cohesionless soils such as SW or GW, $e_{max} - e_{min}$ is large, and e_{min} is small; hence, F is large. These soils are easily compacted. In uniform soils such as certain types of SP or GP, $e_{max} - e_{min}$ is small, and e_{min} is large; hence, F is small, and the soil is more difficult to compact. Determination of the relative density of a soil requires measuring its dry density in place, its dry density in its loosest state, and its dry density in the densest state. The density in place and minimum density present no particular difficulty, but a generally accepted method of determining the maximum density of all cohesionless soils has not yet been found (39).

Compaction of Earthen Dams

The necessity for control of construction of embankments to impound water has been recognized for many years. In 1932, Justin (23) wrote:

> An entirely safe and substantial design may be entirely ruined by careless and shoddy execution, and the failure of the structure may be very possibly the result. Careful attention to the details of construction is, therefore, fully as important as the preliminary investigation and design.

The consequences of ignoring control are exemplified by the large number of earthfill dams built in the United States during the first quarter of this century which did not survive the first filling of the reservoir. Records show that most of those dams were constructed without moistening the soil and without applying special compactive effort.

The rapid increase in knowledge of soil mechanics since the year 1925 has resulted in substantial progress toward understanding the factors involved in transforming loose earth into a structural material. During this same period, however, the development of large economical earthmoving machines has increased the placing rate of earthfill many times, thereby intensifying the problem of quality control. Future progress in design economy in the field of earthwork depends not only on advances in soil mechanics and foundation engineering but also to a large extent on good construction practices in accordance with proper specifications. The ability of inspection personnel to understand and conscientiously apply sound control techniques has also become extremely important.

Construction control is obtained by inspection, testing, and reporting. The inspector of foundations and earthwork is charged with the responsibility of assuring that the assigned work is completed in compliance with specifications. Proper control of earthwork requires the use of laboratory facilities. For small dams, these can be either of the portable variety or they can be small field laboratories that can be set up in the vicinity of the site.

Compaction Methods. Discoveries of remnants of earthfill dams indicate that man's first engineering structures were probably made of earth. The ancient earthfill dams were constructed by armies of workmen carrying baskets loaded with soil. Excavation was done manually, and some incidental compaction was obtained on the fill by the tramping feet of the porters. The importance of compaction of the earthfill was first evident in England where, by the year 1820, cattle and sheep were used for this purpose. By the middle of the 19th century, heavy smooth rollers made of concrete or metal were in use in Europe and had also been introduced in the United States.

The first sheepsfoot roller, the "Petrolithic" roller, was patented in the United States in 1906 for use in compacting oil-treated road surfacing. The most notable early use of the sheepsfoot roller for compaction of fills started in 1912 with the construction of storage reservoirs by the oil companies in southern California. This type of roller was found to be the only one which compacted the fill in layers and gave uniform compaction without producing laminations.

Published material on moisture control for rolled fills dates back to 1907 when Bassell (4) wrote:

> Too much or too little (water) is equally bad and is to be avoided. It is believed that only by experience is it possible to determine the proper quantity of water to use with different classes of materials and their varying conditions. In rolling and consolidating of the bank, all portions that have a tendency to quake must be removed at once. . . .

It was not until 1933, however, that a definite procedure for moisture and compaction control was established by Proctor (30).

Embankment Soils. Some dam sites require that a considerable amount of excavation be performed in order to reach a competent foundation. In many cases, the excavated material may be satisfactorily used in some portions of the embankment. Excavations for spillway and outlet works will also produce varying amounts of usable material. A major portion of embankment yardage for an earthfill dam, however, nearly always must be borrowed.

The stability of an embankment is determined by its ability to resist shear stresses, since most failures occur because of sliding along a shear surface. Shear stresses result from externally applied loads, such as lateral pressure and earthquake forces, and from internal body forces caused by the weight of the soil and the embankment slopes. Embankments of granular or noncohesive materials are more stable than those made of cohesive soils because granular soils have a higher frictional resistance and because their greater permeability permits rapid dissipation of pore-water pressures resulting from compressive forces. Compaction curves of cohesionless soils are defined according to Proctor's principles of compaction.

Embankment Properties. Figure 3 includes a typical profile of an earth and rockfill dam. The exterior zones on both the upstream and downstream sides of the dam are comprised of processed or unprocessed rock which protects the interior zones. The interior of the dam consists of a rock transition zone, the impervious zone (cohesive core), and a sand and gravel (cohesionless) zone.

The basic properties required on the material for the impervious core of a zoned embankment (or for a homogeneous embankment) are:

1. It must be sufficiently impervious to prevent excessive loss of water through the dam.
2. It must be capable of being placed and consolidated to give a practically homogeneous mass which is free from potential paths of percolation.
3. The soil must develop a maximum practical shear strength under compaction and maintain it after filling of the reservoir.
4. It must not consolidate, soften, or liquefy upon saturation.

Maximum density is desirable in the soil. However, it is equally important to limit pore pressures that would lower effective vertical stresses and shearing strength. Material is therefore often placed at slightly drier than optimum water content. This results in densities slightly less than the Proctor maximum and provides lower plasticity which hinders good adherence to the foundation and makes the material more susceptible to cracking. A compromise is therefore necessary to suit conditions at a particular site.

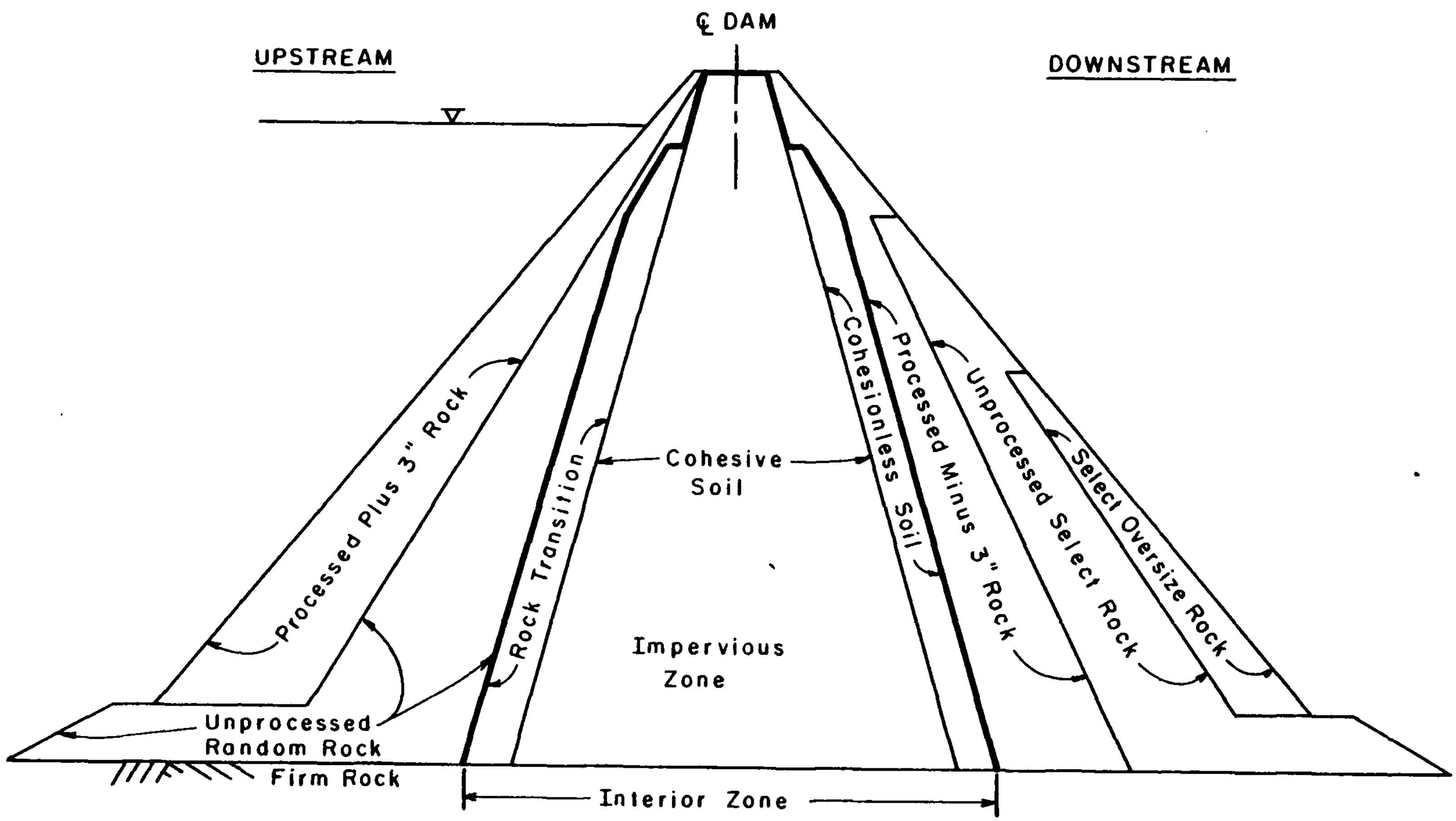


Figure 3. Typical Profile of Dam Illustrating Types of Fill Materials That Are Used

The coarse-grained, permeable-type soils used in the other major zones of the dam are most effectively compacted by vibration when the material is either perfectly dry or when it is nearly saturated with water. The latter method is usually the most practical in the field, since perfectly dry material seldom occurs naturally. The shear strength of permeable soils depends almost entirely on the value of the angle of internal friction of the soil. Cohesion is negligible, and pore-water pressures are never greater than hydrostatic pressure because of the free drainage of the soil. The angle of internal friction is a function of the size, shape, and gradation of the grains; for a given cohesionless soil, its magnitude varies significantly with the void ratio (39).

Statistical Control of Dam Embankment Compaction

Statistical evaluation of the results of control tests was reported by F. J. Davis in 1953 at the Third International Conference on Soil Mechanics and Foundation Engineering in Switzerland when he called attention to errors and misconceptions arising from arithmetic averaging of the results of control tests and proposed statistical methods of evaluation similar to those commonly used for quality control in industry. He proposed use of cumulative frequency plots for establishing allowable limits of variation and emphasized that the use of statistical methods requires standardized sampling and testing procedures for a particular project, separate analysis for each borrow area and for each compaction method or compactive effort, and the elimination of nonrepresentative samples and tests (39).

Using the normal distribution curve (Figure 4) as the statistical model for the control of density and moisture content, Davis in 1966 used appropriate work sheets and cumulative frequency plots to evaluate the control that was achieved on several dam projects. He concluded that moisture control can be based on a standard deviation of less than ± 1.5% and density control can be based on a standard deviation of less than ± 3.0% (39).

Turnbull, Compton, and Ahlvin in 1966 reported in the Journal Soil Mechanics and Foundations Division, ASCE on the variation of density and moisture parameters on several Corps of Engineers projects. They concluded that rather substantial and consistent variations occur which are larger than earthwork designers generally expect. They anticipated that substantial advantages would result from the adaption of statistical methods to soil compaction control. However, they pointed out that entirely satisfactory structures had been built in the past without the use of statistical quality control methods, and stated that current methods would continue to be useful in evaluating construction quality (39).

Smith and Prysock in 1966 reported on a research project in the Journal Soil Mechanics and Foundations Division, ASCE that involved randomly sampling accepted embankment material at 50 locations from each of three highway projects in the state of California. Smith and Prysock agreed that variation in earthwork compaction would be less on well-controlled jobs and greater on poorly controlled jobs. However, they emphasized that compaction distribution curves for a particular job should not be used to compare or evaluate the degree of control

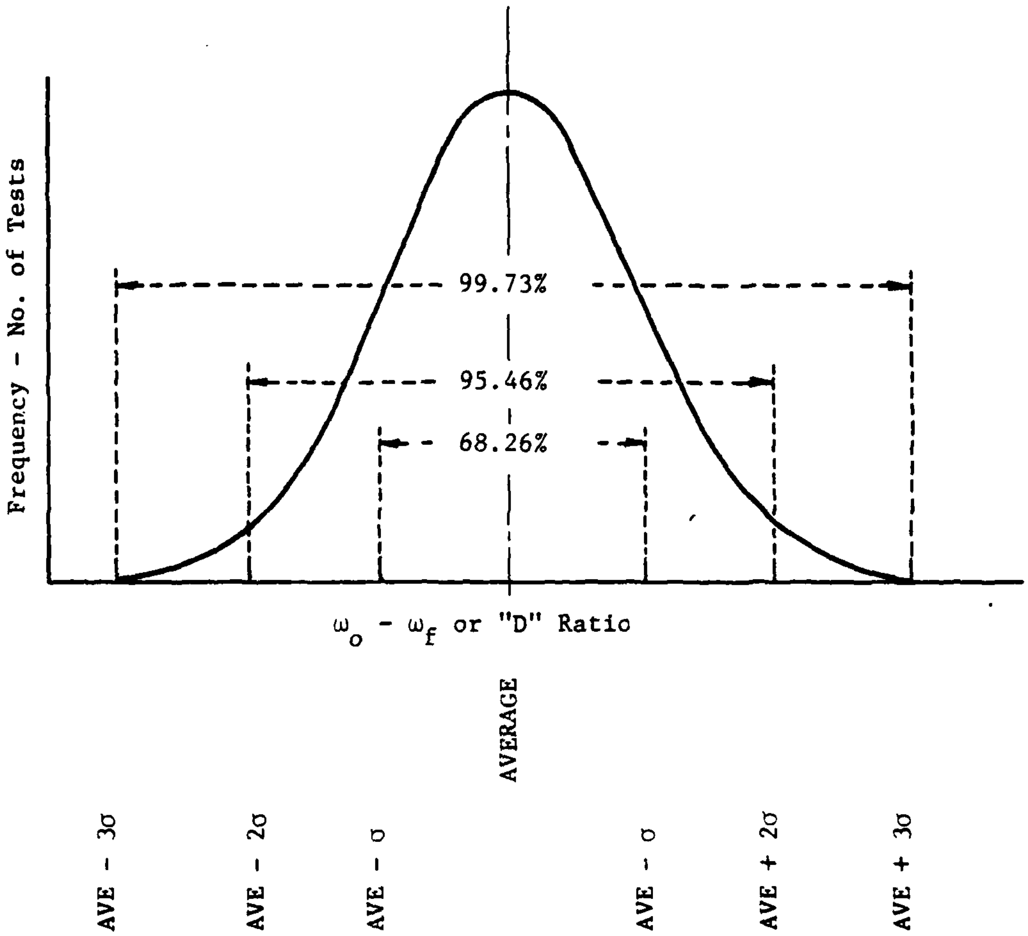


Figure 4. Typical Normal Distribution (37)
(Applicable to both moisture content and density)

ω_o = optimum moisture content
ω_f = fill moisture content
"D" Ratio = ratio of fill dry density to maximum laboratory dry density
σ = standard deviation

employed on another job unless field conditions, including embankment materials, were similar (39).

Abdun-Nur pointed out in 1966 in the Journal Soil Mechanics and Foundations Division, ASCE that the term "quality control" is not applicable for acceptance testing by the owner's personnel, which should be termed "engineering control" or "acceptance control." He stated that quality control (as developed by industry) is possible only through the use of probability and statistical principles, and that it should be left in the hands of the contractor who is the only one who can control the work (39).

The practicability of specifying compaction control using statistical concepts was discussed by de Mello, Silveria, and Silveria, in 1960 at the First Pan-American Conference on Soil Mechanics and Foundation Engineering in Mexico, who used frequency curves for analyzing compaction data from Tres Marias and Santa Branca Dams in Brazil. They considered that there were three basic methods of reducing the percentage of density test values below a given specifications limit: (1) shift the entire field compaction curve by increasing the compactive effort; (2) decrease the standard deviation of the lot (and of the fill) by greater uniformity of construction; and (3) increase the number of tests per lot on which the decision to recompact is based. All of these methods involve additional cost which can be compared with the alternative of not attempting to improve the quality of the fill, but making due compensation for this alternative in the design (39).

Summary

The soil compaction factors discussed must be understood before an effective process control procedure for compaction can be developed. Variability of soils inherently presents unique problems to the compaction process. Each soil has its own moisture-density curve for a given compactive effort. Cohesive soils behave differently than cohesionless soils when compacted, and therefore, must be treated separately from cohesionless soils.

Compaction of earthen dams has changed significantly with the advent of better compaction equipment and improved compaction methods. The effective process control procedure must also incorporate these factors.

Statistical control of compaction was first reported in 1953. Studies anticipated that substantial advantages would result from the use of statistical methods in soil compaction control.

Chapter 3, which follows, provides an analysis of the statistically based theory and techniques which may be used in process control. Major emphasis is placed on the technique known as variable control charts. Several types of variable control charts are introduced. Control chart equations and explanations are presented as background information for a contractor who is interested in using this process control technique.

CHAPTER 3

PROCESS CONTROL THEORY

Philosophy of Process Control

Process control can be defined as "a method based on the application of statistics used to regulate the uniformity of a material, product, or process (27)." From the consumer's viewpoint, the objective of process control is to minimize the production of defective material and, hence, to improve the general quality of the product. Soil which has been incorporated into a finished embankment and is later found to be unsatisfactory cannot be easily replaced. Process control conforms to the familiar adage that "an ounce of prevention is worth a pound of cure." The underlying intent of process control from the contractor's viewpoint is to insure that his compactive effort is accepted without penalties. By maintaining a satisfactory process control program, the contractor should know whether he is furnishing the proper level of quality. Intermediate checks during the compaction process provide valuable information which enables him to quickly identify and correct any problems which may occur. Only through rapid and frequent checks on his process can he protect himself from possible economic loss or delays.

Effective process controls also benefits the contractor in the following two specific ways. The first deals with the seller's risk which is inherent in any acceptance plan which the owner of the project may use. This risk is defined by the particular level of variability which is used in the design of the acceptance sampling plan. Any

change from the assumed process variability affects the risks used to design the acceptance plan. An increase in variability above that used in the acceptance plan will result in a larger seller's risk. As a result, the contractor will have more acceptable material rejected. Reduced variability (i.e., increased uniformity) results in a lower seller's risk. In most cases, the seller's risk can be greatly reduced by even a relatively small improvement in uniformity (28). Therefore, the contractor benefits by maintaining process controls that reduce the variability in his process.

The second benefit to the contractor deals with another aspect of improved uniformity. In many acceptance plans, the average quality level that is acceptable is a function of the sample standard deviation. The lower the variability (i.e., the range), the closer the contractor may operate to the limiting specification value. Thus, the contractor can save money through improved uniformity of operation by not only decreasing his chances of rejection, but also by being able to operate closer to the lower average quality level.

The Control Chart Technique

The one thing that is certain about embankment compaction is that variability of compactive effort will occur, regardless of the type of measurements which are made. The variability arises from a number of sources such as: (1) type of roller used; (2) weight of roller; (3) soil type; (4) moisture content; and (5) changes in the characteristics of the soil.

A recognized principle of statistical quality control is that there are two broad sources of variability. The first is called a

system of chance causes. This type of variation is inherent in any particular method of production and inspection. It is usually not economical to control or eliminate this source of variability since major process revisions are often required (32).

The second source of variability is called a system of assignable causes. An assignable cause is usually a result of some type of error or change in the process. Its effect in contributing to variation is of such importance that the expenditure of time and money for its identification is almost always justified.

Function of Control Charts. One of the problems associated with the assignable cause system is identifying when an assignable cause is acting on the system. One method which may be used to distinguish between chance and assignable causes of variation is the statistical control chart technique (31). This technique provides a graphical representation of the variations in measurements made on samples of the process. Sometimes a control chart will show that a change should be made in the process. At other times, a control chart will show that a change should not be made. Control charts not only indicate when established limits have been exceeded, they also provide a means of anticipating and correcting causes which would tend to result in a defective product.

Description of Control Charts. According to Duncan (11:316), "a control chart is a device for describing in concrete terms what a state of statistical control is; second, a device for attaining control; and, third, a device for judging whether control has been attained." This is accomplished by establishing a control chart such as that shown

in Figure 5. It will be noted that this chart has three horizontal lines. The central line corresponds to the average or target value of a measurable characteristic. The extreme lines are representative of the upper and lower control limits. These limits are established so that test result values falling between them are assumed to result from the action of the system of chance causes. It should be noted in Figure 5 that the control chart can be subdivided into two phases. The first phase would use the historical period data to establish the central line and the control limits. The second phase would then use the data from the implementation period (which may be used to revise the central line and control limits, as required).

Physically, the statistical control chart may be viewed as a normal distribution turned on its side with the horizontal axis being test results, time, or some other indication of order and the vertical axis being the measurable quality characteristic. Statistical interpretations made from control charts are based on the normal distribution. Most material attributes are normally distributed. If subgroup size $n = 1$ is used, the test data must be normally distributed. Subgroup sizes of n greater than 1 will follow the Central Limit Theorem, which states:

> Irrespective of the shape of the distribution of a universe, the distribution of average values, $\bar{X}$'s, of samples of size n, ($\bar{X}_1$, $\bar{X}_2$, $\bar{X}_3$, ..., $\bar{X}_k$), drawn from that universe will tend toward a normal distribution as n tends toward infinity (18:230).

The central line is equivalent to the mean or target value ($\bar{X}$) and the control limits are set at a certain number of standard deviations (σ) from the central line. For a normal curve, practically all measured results (99.73%) can be expected to fall within the limits $\bar{X} \pm 3\sigma$.

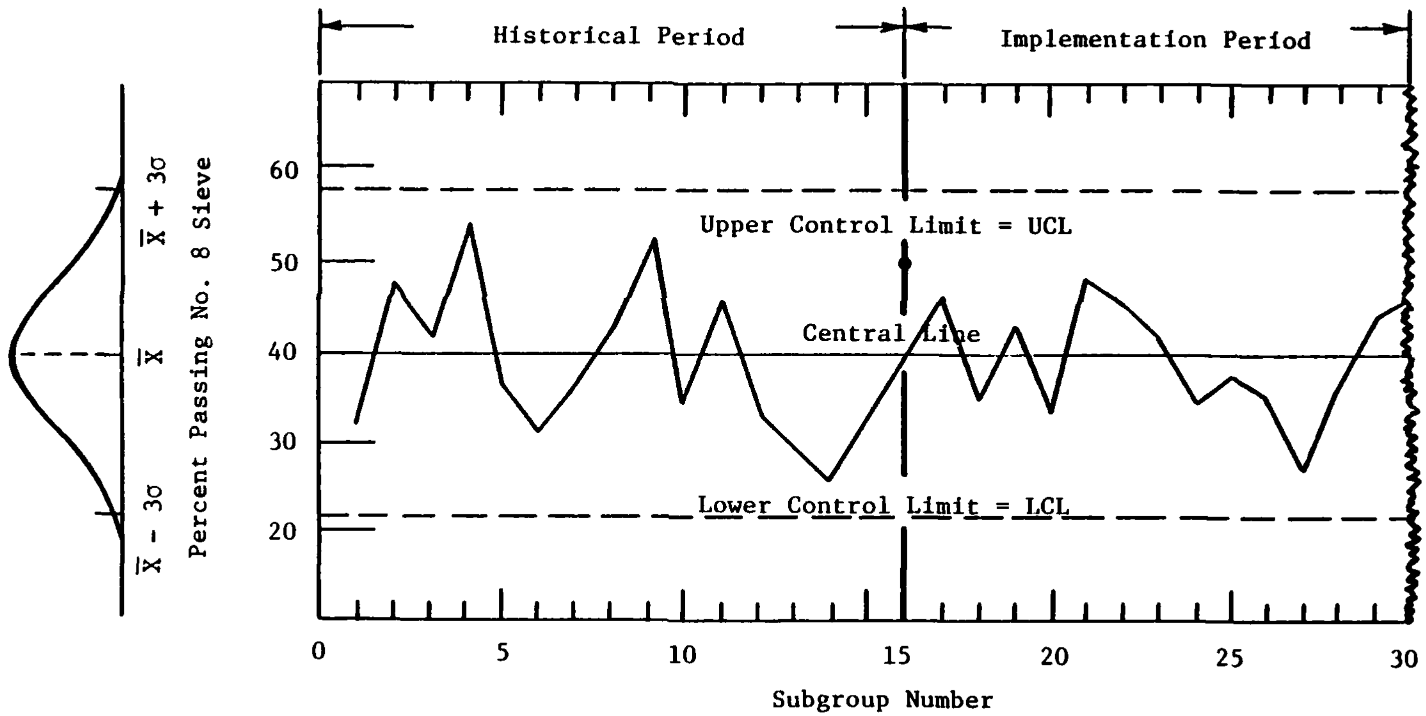


Figure 5. Control Chart Format (18)

Therefore, if values are found outside these control limits, it is a signal that either a rare event has occurred or that the material characteristic has changed. In any case, such an observation is a signal for investigation.

In order to plot the control chart, samples of size n are randomly selected from the process. It is important to note that all concepts underlying statistical control charts are based on random sampling. The most common statistical control charts require subgrouping of samples into sizes of $n > 1$.

There are a number of rules which can be used to determine how to divide the data into logical subgroups. The choice of the size of the subgroup depends on the type of process and the inclination of the person who is preparing the control chart. Less reliable and more variable results are obtained as the subgroup size decreases. The overriding criteria for the determination of the subgroup size n is that all the values within a subgroup must be logically related.

One criterion used is to group data that is produced (as nearly as possible) at one time into the same subgroup. For example, if a contractor is taking density tests, and the subgroup size is two, he might take two density samples within close proximity of each other. Then, later in the day, when a second random sampling time is indicated, he might take two more samples from an area utilizing identical compaction equipment, number of passes, moisture content, and soil type.

A second subgrouping criterion considers the grouped data to be representative of the compaction over a given period of time. In this case, for a subgroup size of two, a contractor might take two density

samples that are randomly spaced over the morning shift and two more tests during the afternoon shift.

Once the basis for subgrouping has been established, subgroups of the same size n are randomly selected at frequent intervals in the process. The frequency depends upon the nature of the process and the availability of manpower and testing facilities. The sample averages of the subgroup results are plotted on the control charts in the order in which they were sampled. When plotted points fall outside the control limits, a problem which may necessitate a process change is indicated. When a trend of points inside the control limits is identified, an adjustment in the process may also be necessary. The closer the plotted values are to the central line, the better the control of the product.

A process is termed to be in statistical control when the process level, or some property of the process output, remains within an expected tolerance range over a period of time. This process level could be the specified moisture content or the specified maximum dry density. It is natural, due to chance causes of variation, that the individual tests taken from the process will differ from the average or target value. The size of these differences is a direct result of the process, and is called the process capability (21). In effect, the process capability is simply the range between the two control limits on a statistical control chart.

<u>Types of Control Charts</u>. There are two general types of control charts. The first is a control chart for attributes. Attributes are usually visually inspected properties such as cracks, scratches, missing

parts, or materials inspected by go or no-go gauges. No actual measurements are recorded. The characteristic under inspection is merely classified qualitatively as conforming or not conforming to a specified requirement. To compensate for the loss in information that results when measurements are not recorded, a much larger subgroup size is required to achieve the desired sensitivity (10). This increased sampling requirement is most applicable for rapid and inexpensive test methods found in the manufacturing industry. However, the most accurate compaction tests are done in the laboratory and are usually very time consuming. Consequently, attribute application appears to have very limited application in embankment compaction.

The second type of control chart is the control chart for variables. A variable control chart records the actual measured quality of the characteristic. Although more effort is usually required in taking and retaining a measurement, the greater information supplied by variable sampling enables a desired level of sensitivity to be obtained with fewer samples than required with the attribute approach. Since most compaction specifications and control procedures are based on measured properties, cost associated with test procedures make it imperative that the maximum value of the measurements be utilized.

Eventually, with the development of rapid test methods, such as the nuclear densometer, the use of attribute control charts may become feasible. However, control charts for variables will be recommended in this thesis since they appear to be the most valuable in embankment construction at the present time.

Variable Control Charts

It has been previously stated that the function of a control chart is to provide a means for distinguishing between chance and assignable sources of variation. To do this, control limits representing the normal degree of variation expected in the controlled process are set so that points falling outside these limits are attributed to assignable causes. In order to describe the process completely, at least two indicators of the process are required. The first indicator is a measure of the central tendency of the process. The most frequently used tool in control charts is the arithmetic mean, $\overline{X}$. The second indicator measures the dispersion or spread of the process. There are two basic tools employed for this purpose. Probably the most well known measure of dispersion is the standard deviation σ . However, its complicated formula has proved to introduce computational difficulties in the field unless expensive computing equipment is available. A second measure of dispersion, equally sensitive for estimating the process variability, is the range R . The range of a subgroup is computed by subtracting the smallest test result from the largest test result in the subgroup. Because of its ease in calculation, the range is used most often to control variability in control charts.

Types of Variable Control Charts. It should be emphasized that there are many different types of variable control charts that have been developed for manufacturing processes. Some of these control chart techniques may not be practical or even valuable for the earthwork compaction field due to the different circumstances and conditions which exist.

It is therefore the intent of this chapter to provide a basic understanding of the most useful and readily adaptable control chart techniques. The contents of the remainder of this chapter will therefore be limited to the following types of control charts:

1. Control Chart for Individuals
2. Control Chart for Moving Range
3. Control Chart for Moving Averages (Trend Indicator Chart)
4. Shewhart Control Charts
    a. Control Chart for Averages ($\overline{X}$-chart)
    b. Control Chart for Ranges (R-chart)

Control chart for individuals

Possibly the simplest control chart is the control chart for individuals (2), in which individual observations are plotted one-by-one. This type of control chart has been found most useful when only one observation is used to describe the process for a particular amount of material. This often occurs when sampling and testing is expensive, time consuming, or destructive in nature. The variability of the process for this type of a chart is estimated by the moving range between successive observations arranged in chronological order. One limitation to this simple control chart is that it requires the underlying distribution of individual values to be fairly symmetrical. A second limitation is that the plotted observations, being individual results, tend to fluctuate about the central line. This usually makes the interpretation of trends difficult.

Trend indicator chart

This control chart technique is often used in conjunction with control charts for individuals. It is sometimes called a control chart for moving averages (18). This type of chart smooths out the normally expected point-to-point fluctuations of individual test results. It achieves this effect by plotting the moving average of several test results. For example, when considering the moving average of several test results, the first plotted point would be the average of the second, third, and fourth results, etc. The more successive points included in the moving average, the greater the smoothing effect and the more the chart emphasizes trends. This chart is often used to reduce the frequency of process adjustments caused by premature judgments based on individual samples.

Shewhart control charts

This type of chart was originally developed by W. A. Shewhart of Bell Telephone Laboratories in the early 1930's (18). This technique has proven to be very effective in identifying the presence of assignable causes. It requires test results to be grouped into subgroups of size $n > 1$. All interpretations are based on the normal distribution. According to Grant and Leavenworth (18), Shewhart has proven that under certain circumstances the distribution of sample means of subgroup sizes as small as $n = 4$ for extremely non-normal distributions result in distributions which very closely resemble a normal distribution. Therefore, if subgroups of size $n = 4$ were used under the conditions set up by Shewhart, one would be assured that the probability relationships used in interpreting these control charts are fairly accurate even if the distribution being sampled is non-normal.

In order to employ the Shewhart technique, two control charts are required. The first control chart is known as the control chart for averages ($\overline{X}$-chart). This chart controls the central tendency of the process by examining the change in process average between subgroups. The second control chart controls the dispersion of the process by examining the variability within the subgroups. Either a control chart for ranges (R-chart) or a control chart for standard deviation (σ-chart) may be used for this purpose.

Control Limits. The key element in the use of the statistical control charts is the proper designation of the control limits for a given process. As noted earlier, the purpose of control limits is to provide a dividing line between expected chance variation and assignable cause variation. In any type of decision problem, the risk of making a wrong decision is present. In control chart interpretations, this error in judgment may take one of two forms. The first form occurs when the control limits are set so far apart (4σ, for instance) that they become too insensitive to detect the presence of assignable causes. The second form of error occurs when the control limits are set too close together (2σ, for instance) that they produce false indications of assignable causes. The choice of these limits should strike an economic balance between the cost due to the error of hunting for an assignable cause when one is not present, and the cost of leaving the process alone when an adjustment is really needed. Grant and Leavenworth (18) point out that in most cases, the choice of three-sigma limits provides this economic balance.

To establish control limits, values for the population mean $\overline{X}'$ and the population standard deviation σ' are needed. The two basic ways in which these parameters are usually obtained are:

1. $\overline{X}'$ and σ' are known or given in the material specification.
2. $\overline{X}'$ and σ' are estimated from past or current data.

The first case occurs less frequently than the second. Usually, a large number of statistically valid samples are required in order to define the population parameters $\overline{X}'$ and σ'. If the contractor has been collecting random samples for a long period of time on essentially the same process, he may choose to use this data to compute these population parameters. In the writer's opinion, the assumption of a long period of essentially controlled conditions is doubtful in the embankment compaction process. A relatively short "historical period," or a concentrated period of sampling, may therefore have to be used out of necessity. The concentrated period of sampling may consist of increasing the frequency and number of tests during the early stages of the construction season in order to give the contractor process control parameters. These parameters may also be assumed known if a compaction contractor defines control limits in terms of the $\overline{X}'$ and σ' that were used to establish the agency's acceptance plans.

The second case of estimating the population parameters appears more frequently. It usually occurs whenever a contractor is setting up control charts for the first time on a construction project. A frequent pitfall encountered in estimating these parameters is the incorrect or naive use of past data. Very often, this past data represents routine

compaction control tests that were taken on a non-random basis. Sometimes this data represents only those tests that were classified as passing results. In either case, this type of data usually does not provide a true estimate of the population parameters. Therefore, in estimating these parameters from past or current data, the samples should be both random and truly representative.

Manufacturing control chart theory requires large collections of subgroups of size $n > 1$ to be used when computing control limits which are to be used for guiding future production. Rice (31:63) illustrates this concept as follows:

> Sampling errors vary inversely as the square root of the number of observations. Holding for large samples as well as small ones, this means that, in a sample 4 times as large as a selected one, the error of estimate of the average will be one-half as great; for a sample 100 times as large, the error will be one-tenth as great. Before control-chart limits are extended as guides for the future, they should contain as small a sampling error as is economically possible. The size of that error depends upon the total number of observations, N, used in calculating the limits. During the experimental period, where assignable causes are being hunted down, as few measurements as seem necessary may be made, but, once the chart is set for predicting the future, at least 100 observations should be used in calculating the mean and the limits. Then, if the sample size is 3, the number of samples m should be at least 34; if $n = 4$, m should be at least 25; if $n = 5$, m should be at least 20.

It has been previously stated that the major difference between sampling from a manufacturing process and from the embankment compaction process is the time and expense involved in sampling and testing the control characteristics. Whereas the ideal subgroup size may be four, six or eight from a statistical standpoint, it probably would not represent a very practical construction approach. Therefore, on a dam

construction project, it may be necessary to use smaller subgroup sizes (n) and fewer total number of observations (N) in estimating the values of $\overline{X}'$ and σ' than is ideally indicated.

In setting up initial control limits based on a minimal amount of data, Grant and Leavenworth (18) indicate that it is necessary to view these control limits as being temporary with the intention of revising them when sufficient data has been accumulated. Since there is usually no way of determining whether statistical control was present when the initial samples were collected, it is possible that the control limits thus calculated may not truly represent the process capability.

Therefore, the usual practice is to view these initial control limits as trial control limits. These trial control limits should be computed from data which is free from assignable causes of variation. Otherwise, the control limits will be set so wide that their full potential will not be realized. To assure that assignable causes are not influencing the location of trial control limits, the initial subgroups and trial limits are plotted on the control charts. If it appears that the subgroups which were used to compute the trial control limits exceed them, then the trouble causing those extreme points should be investigated. If the investigation results in the identification and correction of assignable causes responsible for those out-of-control points, then those points should be removed and new control limits should be calculated. If these new trial limits show that additional subgroups are out of control, the appropriate subgroups should also be removed if assignable causes are responsible, and the control chart should be repeated. It should be emphasized that points

outside the trial control limits should not be removed unless the assignable cause of variation which is responsible for those out-of-control points can be corrected. If no assignable cause is found, those subgroups should remain in the control chart limit calculations.

The usual procedure is, therefore, to implement these trial control limits for a limited amount of future production with the expectation of eliminating any detectable assignable causes. When a sufficient amount of control chart data has been accumulated, the original control limits may be revised based on more recent data. Trial control limits merely act as a starting mechanism. Their value in identifying points influenced by assignable causes is limited because the data used in the trial control limit calculations has become historical in nature.

Control Chart Equations. It has been stated that control charts strive to provide information about both the central tendency and the dispersion of a process. Information about the central tendency may be provided by means of an $\overline{X}$-chart, a trend indicator chart, or a chart of individual observations. Information about the dispersion of the process is provided by means of R-charts because of their ease of calculation. As previously noted, a standard deviation (σ) chart could be used instead of an R-chart, but since it has been shown that it does not provide a better estimate of the variability than the range for subgroups of size $n < 15$ (18), it is usually not recommended.

A statistical control chart relies on the fact that for all practical purposes, the distribution of measurements about a mean or

central value occurs within three-sigma of that mean value. Grant and Leavenworth (18:87) summarize the basic equations for the control limits for the different types of control charts as follows:

1. Individual observations

   $\bar{X}' \pm 3\sigma'$

2. Sample means, $\bar{X}$ (subgroups of size n > 1)

   $\bar{X}' \pm 3\sigma_{\bar{X}}$, where $\sigma_{\bar{X}} = \frac{\sigma'}{\sqrt{n}}$ = standard error of the mean, therefore, $\bar{X}' \pm \frac{3\sigma}{\sqrt{n}}$

3. Ranges (subgroups of size n > 1)

   $\bar{R} \pm 3\sigma_R$, where σ_R = standard deviation of the individual subgroup ranges

<u>Control charts for individuals</u>

Two types of control charts may be developed using individual observations. One chart plots the individual observations as a measure of central tendency. The second chart plots the moving range between successive individual observations as a measure of the process dispersion. Control limits are established in either of the following two ways: (1) population standards $\bar{X}'$ and σ' are given or assumed, and (2) population standards $\bar{X}'$ and σ' are estimated from past or current data.

The following formulae are used to calculate the three-sigma control limits for individuals when standards are given or assumed (2:78):

1. <u>Chart for Individuals: $\overline{X}'$ and σ' known</u>

Central Line = $\overline{X}'$

Upper Control Limit = UCL_X = $\overline{X}' + 3\sigma'$

Lower Control Limit = LCL_X = $\overline{X}' - 3\sigma'$

2. <u>Moving Range, Chart of Two Consecutive Observations: $\overline{X}'$ and σ' known</u>

Central Line = $d_2\sigma'$

Upper Control Limit = UCL_R = $D_2\sigma'$

Lower Control Limit = LCL_R = $D_1\sigma'$

where d_2, D_1, and D_2 = constants from Tables 1 and 2 for subgroup size $n = 2$.

When the standard parameters $\overline{X}'$ and σ' must be established from past or current data, the moving range between individual observations is used to estimate σ' . The following formulae are used to calculate the three-sigma control limits (2:78):

1. <u>Chart for Individuals: $\overline{X}'$ and σ' unknown</u>

Central Line = $\overline{X}_1$

Upper Control Limit = UCL_X = $\overline{X}_1 + 3\dfrac{\overline{R}_2}{d_2}$ = $\overline{X}_1 + 2.66\ \overline{R}_2$

Lower Control Limit = LCL_X = $\overline{X}_1 - 3\dfrac{\overline{R}_2}{d_2}$ = $\overline{X}_1 - 2.66\ \overline{R}_2$

2. <u>Moving Range Chart of Two Consecutive Individual Observations: $\overline{X}'$ and σ' unknown</u>

Central Line = $\overline{R}_2$

Upper Control Limit = UCL_R = $D_4\overline{R}_2$ = $3.27\ \overline{R}_2$

Lower Control Limit = LCL_R = $D_3\overline{R}_2$ = 0

TABLE 1

FACTORS FOR ESTIMATING σ' FROM $\bar{R}$
FROM PAST OR CURRENT DATA
[from Grant and Leavenworth (18:644)]

Number of Observations in Subgroup n	Factor Estimate from $\bar{R}$ $d_2 = \bar{R}/\sigma'$
2	1.128
3	1.699
4	2.059
5	2.326
6	2.534
7	2.704
8	2.847
9	2.970
10	3.078
11	3.173
12	3.258
13	3.336
14	3.407
15	3.472

TABLE 2

FACTORS FOR COMPUTING THREE-SIGMA CONTROL LIMITS
WHEN STANDARD PARAMETERS $\bar{X}'$ AND σ' ARE KNOWN
[from Grant and Leavenworth (18:647)]

Number of Observations in Subgroup	Factor for $\bar{X}$ Chart	Factors for R Chart	
		Lower Control Limit	Upper Control Limit
n	A	D_1	D_2
2	2.12	0.00	3.69
3	1.73	0.00	4.36
4	1.50	0.00	4.70
5	1.34	0.00	4.92
6	1.22	0.00	5.08
7	1.13	0.20	5.20
8	1.06	0.39	5.31
9	1.00	0.55	5.39
10	0.95	0.69	5.47
11	0.90	0.81	5.53
12	0.87	0.92	5.59
13	0.83	1.03	5.65
14	0.80	1.12	5.69
15	0.77	1.21	5.74

$$\text{where } \bar{X}_1 = \frac{\sum_{i=1}^{m} X_i}{m} \text{ ; } X_i \text{ obtained from historical data}$$

$$\bar{R}_2 = \frac{\sum_{i=1}^{m} R_i}{m} \text{ ; } R_i \text{ obtained from difference between successive individual observations}$$

d_2, D_3, D_4 = constants obtained from Tables 1 and 3 for subgroup size $n = 2$

Although Tables 1 and 2 were used to calculate the moving range of size $n = 2$ for the chart of individual case, it should be noted that these tables will also be used for the other types of control charts which may use larger subgroup sizes.

Trend indicator chart

This chart, often used to supplement the control chart for individuals by identifying trends, plots a moving average of test results. Any convenient number of test results may be used in the moving average. The control limits are established by computing an average moving range for the number of observations included in each successive moving average. It should be noted that the trend indicator chart is not limited in its use to individual observations. It may be of value in identifying trends present in Shewhart (i.e., $n > 1$) control charts.

The three-sigma control limits may be calculated from the following formulae when the standards $\bar{X}'$ and σ' are known (21:4-17):

TABLE 3

FACTORS FOR COMPUTING THREE-SIGMA CONTROL LIMITS
WHEN STANDARD PARAMETERS $\bar{X}'$ AND σ' ARE UNKNOWN
[from Grant and Leavenworth (18:645)]

Number of Observations in Subgroup	Factor for $\bar{X}$ Chart	Factors for R Chart	
		Lower Control Limit	Upper Control Limit
n	A_2	D_3	D_4
2	1.88	0.00	3.27
3	1.02	0.00	2.57
4	0.73	0.00	2.28
5	0.58	0.00	2.11
6	0.48	0.00	2.00
7	0.42	0.08	1.92
8	0.37	0.14	1.86
9	0.34	0.18	1.82
10	0.31	0.22	1.78
11	0.29	0.26	1.74
12	0.27	0.28	1.72
13	0.25	0.31	1.69
14	0.24	0.33	1.67
15	0.22	0.35	1.65

1. Trend Indicator Chart: $\overline{X}'$ and σ' known

Central Line = $\overline{X}'$

Upper Control Limit = $UCL_{\overline{X}_k} = \overline{X}' + \frac{3\sigma'}{\sqrt{kn}}$

Lower Control Limit = $LCL_{\overline{X}_k} = \overline{X}' - \frac{3\sigma'}{\sqrt{kn}}$

where k = the number of observations or subgroups included in the moving average

n = number of observations included in the subgroups; for individual observations, n = 1

When the standards $\overline{X}'$ and σ' must be estimated from past or current data, the three-sigma limits are calculated from the following formulae (21:4-17):

1. Trend Indicator Chart: $\overline{X}'$ and σ' unknown

Central Line = $\overline{X}_1$

Upper Control Limit = $UCL_{\overline{X}_k} = \overline{X}_1 + \frac{3\overline{R}}{d_2\sqrt{kn}}$

Lower Control Limit = $LCL_{\overline{X}_k} = \overline{X}_1 - \frac{3\overline{R}}{d_2\sqrt{kn}}$

where $\overline{X}_1 = \frac{\sum_{i=1}^{m} X_i}{m}$; X_i obtained from historical data

$\overline{R} = \frac{\sum_{i=1}^{m} R_i}{m}$; R_i obtained from difference between successive individual observations

k = number of individual observations in a moving average when trend indicator chart is composed of individuals

k = number of subgroups in a moving average when trend indicator chart is composed of subgroups

n = number of observations included in the subgroups (for individual observations, $n = 1$)

d_2 = constant obtained from Table 1 for estimating σ'. When the chart is composed of individuals, d_2 is based on k, the number of individual observations in the moving average. When the chart is composed of subgroups, d_2 is based on n, the size of the subgroup.

Shewhart control charts

Shewhart control charts required subgroups of size $n > 1$ to be selected in a way that makes each subgroup as homogeneous as possible and that gives a minimum opportunity for variation to occur within the subgroup. The success of the Shewhart technique depends in large measure on the selection of these subgroups.

When the standard parameters $\overline{X}'$ and σ' are known or assumed, the following formulae are used to calculate the three-sigma control limits (18:87):

1. $\overline{X}$ chart: $\overline{X}'$ and σ' known

   Central Line = $\overline{X}'$

   Upper Control Limit = $UCL_{\overline{X}} = \overline{X}' + A\sigma'$

   Lower Control Limit = $LCL_{\overline{X}} = \overline{X}' - A\sigma'$

2. <u>$\overline{R}$ Chart: $\overline{X}'$ and σ' known</u>

Central Line $= d_2\sigma'$

Upper Control Limit $= UCL_R = D_2\sigma'$

Lower Control Limit $= LCL_R = D_1\sigma'$

where A, D_1, D_2, d_2 = constants obtained from Tables 1 and 2 for various subgroup sizes n

When it is necessary to estimate the standard parameters $\overline{X}'$ and σ', the following formulae are used to calculate the three-sigma control limits (18:87):

1. <u>$\overline{X}$ Chart: $\overline{X}'$ and σ' unknown</u>

Central Line $= \overline{\overline{X}}$

Upper Control Limit $= UCL_{\overline{X}} = \overline{\overline{X}} + A_2\overline{R}$

Lower Control Limit $= LCL_{\overline{X}} = \overline{\overline{X}} - A_2\overline{R}$

2. <u>R Chart: $\overline{X}'$ and σ' unknown</u>

Central Line $= \overline{R}$

Upper Control Limit $= UCL_R = D_4\overline{R}$

Lower Control Limit $= LCL_R = D_3\overline{R}$

where $\overline{\overline{X}} = \dfrac{\sum_{i=1}^{m} \overline{X}_i}{m}$ = grand mean of "m" group averages $\overline{X}_i$ of the historical data

$\overline{R} = \dfrac{\sum_{i=1}^{m} R_i}{m}$ = average range of "m" group ranges R_i of the historical data

$\overline{X}_i$ = the mean value of all measurements within each subgroup of size n

R_i = the range of each subgroup of size n

m = number of subgroups of size n used in the control chart calculation

A_2, D_3, D_4 = constants obtained from Table 3 for various subgroups sizes n

Control Chart Interpretations. As noted earlier, the purpose of the control chart is to identify the presence of an assignable cause. This presence is indicated by signs of lack of control in the control chart. Lack of control may be classified into three major categories as follows:

1. Change in average ($\overline{X}'$) with the dispersion (σ') remaining constant.
2. Change in dispersion (σ') with the average ($\overline{X}'$) remaining constant.
3. Change in both average ($\overline{X}'$) and the dispersion (σ').

It should be understood that shifts in population average ($\overline{X}'$) influence control charts in one way, while shifts in population dispersion (σ') affect them in another way. Shifts may be sustained over a period of time, they may be gradual and systematic, or they may be frequent and irregular.

Lack of control may be identified in two ways. The first, and probably most common method, is to consider plotted points falling outside the three-sigma control limits as evidence of lack of control in the process. Theoretically, based on the normal distribution, only one out of 370 points on a control chart should exceed the three-sigma limits as a result of chance alone. Schrock (32) indicates that, in

practice, a process should be considered in statistical control if no points out of 25, not over one point out of 35, and not over two points out of 100 are outside of the three-sigma control limits.

The "out-of-control" point criteria has the advantage of being simple and very rarely indicates signs of lack of control without a real change in the process having taken place. However, used by itself, it often has the disadvantage of being too insensitive to small changes in the process.

For this reason, it is often useful to supplement the "out-of-control" point criteria with evidence given by tests based on the statistical theory of runs. Various types of complicated statistical tests of runs have been developed by mathematicians. The most practical plan for a contractor, however, is to use a few simple rules that depend on the theory of extreme runs. Grant and Leavenworth (18:97, 98) have listed five rules that may be used in conjunction with the "out-of-control" point criteria.

It is assumed that grounds of suspicion exist that the population parameter has shifted (i.e., the process has gone "out of control"):

1. Whenever, in 7 successive points on the control chart, all are on the same side of the central line.
2. Whenever, in 11 successive points on the control chart, at least 10 are on the same side of the central line.
3. Whenever, in 14 successive points on the control chart, at least 12 are on the same side of the central line.

4. Whenever, in 17 successive points on the control chart, at least 14 are on the same side of the central line.
5. Whenever, in 20 successive points on the control chart, at least 16 are on the same side of the central line.

Grant and Leavenworth (18) point out that if all these rules are used to judge control, the probability of a false indication is greater than if only one of the rules is used. It is therefore recommended that only one rule, usually the first, involving seven successive points, be used in conjunction with the "out-of-control" point criterion.

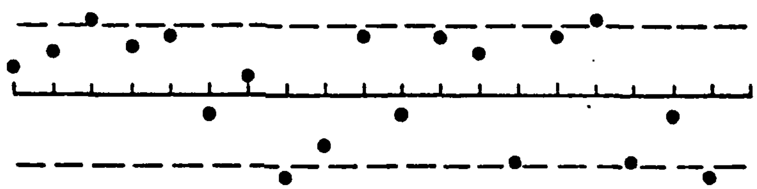
A distinction in the interpretation of trend indicator charts should be noted. The trend indicator chart's function is to indicate trends, not to identify the presence of assignable causes. Since the trend results from combining subgroups into moving averages, the individual subgroups are no longer independent of each other. Therefore, care should be exercised in drawing conclusions from groups of points outside the control limits on trend indicator charts. Similarly, the rules for extreme runs are no longer applicable for trend indicator charts since a common test result is used to compute several successive moving averages.

An intimate knowledge of the process being controlled is vital to the effective use of the control chart. The control chart tells when to look for trouble, but it cannot, by itself, tell where to look or what cause will be found. Figure 6 taken from Grant and Leavenworth (18: 110, 111) illustrates some of the patterns frequently seen on control charts and states some possible causes of these patterns. These figures were developed by Bell Telephone Laboratories as an aid

Some causes affecting $\overline{X}$ chart (stable variability)	Some causes affecting R chart

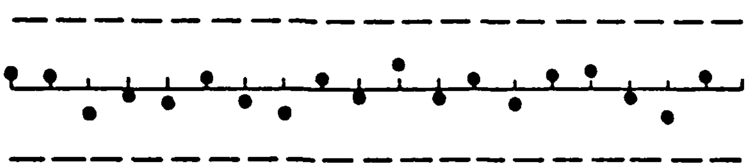
(c) Jumps in process level

1. Change in proportions of materials or sub-assemblies coming from different sources	1. Change in material
2. New worker or machine	2. Change in method
3. Modification of production method or process	3. Change in worker
4. Change in inspection device or method	



(d) High proportion of points near or outside limits

1. Over control	1. Mixture of materials of distinctly different quality
2. Large systematic differences in material quality	2. Different workers using a single R chart
3. Large systematic differences in test method or equipment	3. Data from processes under different conditions plotted on same chart
4. Control of two or more processes on same chart	

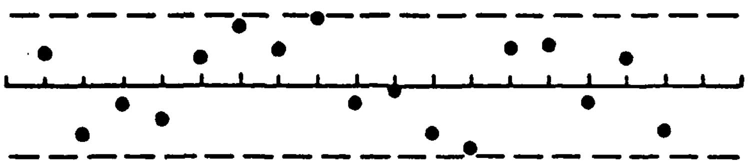


(e) Stratification or lack of variability

1. Incorrect calculation of control limits	1. Collecting in each sample a number of measurements from widely differing universes

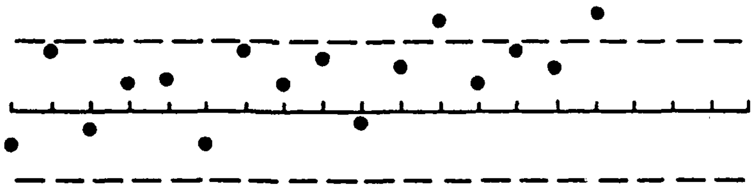
Figure 6. Some Interpretation of Patterns of $\overline{X}$ Charts and R Charts [from Grant and Leavenworth (18:110-112)]

Some causes affecting $\overline{X}$ chart (stable variability)	Some causes affecting R chart



(a) Recurring cycles

Some causes affecting $\overline{X}$ chart (stable variability)	Some causes affecting R chart
1. Temperature or other recurring changes in physical environment	1. Scheduled preventive maintenance
2. Worker fatigue	2. Worker fatigue
3. Differences in measuring testing devices which are used in order	3. Worn tools
4. Regular rotation of machines or operators	
5. Merging subassemblies other processes	



(b) Trends

Some causes affecting $\overline{X}$ chart (stable variability)	Some causes affecting R chart
1. Gradual deterioration of equipment which can affect all items	1. Improvement or deterioration of operator skill
2. Worker fatigue	2. Worker fatigue
3. Accumulation of waste products	3. Change in proportions of subprocesses feeding an assembly line
4. Deterioration of environmental conditions	4. Gradual change in homogeneity of incoming material quality

Figure 6. (Continued)

in training young inspectors and engineers. The listed causes should be used only as a guide to possible action and not as an authoritative listing of the causes of trouble.

Summary

It should be evident that some variability will always be present in construction materials as well as in compaction procedures. Variability is usually the result of two source systems, chance and assignable, acting on the process. The function of control charts is to minimize variation by identifying and eliminating assignable causes. While attribute control charts are often used in the manufacturing industry, variable control charts appear most valuable in the compaction process. Three variable control chart methods were therefore presented in the chapter. Each of these methods require the data to be logically subgrouped, control limits to be calculated, and plotted points to be interpreted as the result of either chance or assignable causes of variation.

Control charts have been used successively by the manufacturing industry for over 40 years. Their value in controlling and limiting production of defective material has usually paid for the cost of maintaining control charts many times over.

In light of these benefits, Chapter 4 presents a general procedure that may be used by contractors to develop a process control system for embankment compaction.

CHAPTER 4

GUIDELINES FOR THE DEVELOPMENT OF A PROCESS CONTROL SYSTEM ON DAM A

The data used in this thesis were obtained from a current United States Army Corps of Engineers dam construction project, which for the purposes of this thesis is identified as Dam A. The data were used to develop the suggested process control system which is discussed in this chapter.

It should be noted at the beginning of this chapter that the development of a process control system by a contractor is typically an implementation and revision procedure. Once an initial system is developed and implemented, it would normally be reviewed for a period of time in order to determine its effectiveness and feasibility. Modifications are then incorporated into the next implementation phase. The time limitations related to this thesis did not allow such a procedure to be applied by the writer. Consequently, only the first phase, involving the initial development of the system, was completed.

Similarly, a statistically valid evaluation of the acceptance criteria used in the Corps of Engineers specification would also have required much more data than the writer was able to obtain in the data collection stage of this thesis. It was therefore decided that the acceptance portion of the specification would not be examined.

It should be noted that the data were not actually collected by the writer, but were obtained during the spring and summer of 1979 from the Corps of Engineers district responsible for Dam A. The

construction material portion of the data for the test results impervious zone is presented in Appendix C.

The procedure which is presented in order to aid a contractor in the development of a process control system for compaction of earthen dam embankments somewhat parallels the actual developmental procedure on a project which would involve the following steps:

1. Assignment of responsibility for process control.
2. Review of the embankment specification.
3. Development of a sampling and testing plan.
4. Selection of documentation techniques.
5. Selection of a format for recording of data.
6. Selection and establishment of the control limits.
7. Selection of the interpretation criteria.
8. Investigation and elimination of assignable causes.
9. Evaluation of the system.

Description of Present Practices on Dam A

Dam A consists of rolled earth and rockfill construction. A typical plan view, profile view, and borrow area location map are shown in Figures 7, 8, and 9, respectively. Dam A will have a maximum height of 296 feet (90.2 meters) and a top length of 2,130 feet (649.2 meters) and will contain approximately 9,875,000 cubic yards (7,550,977 cubic meters) of earth and rock. The controlled spillway, located on the left abutment, will have a crest length of 210 feet (63.3 meters) and will have five gates, each 32 feet (9.8 meters) high and 42 feet (12.8 meters) long. The outlet works, to be cut through the rock in the right abutment, will consist of a 16.33-foot-diameter

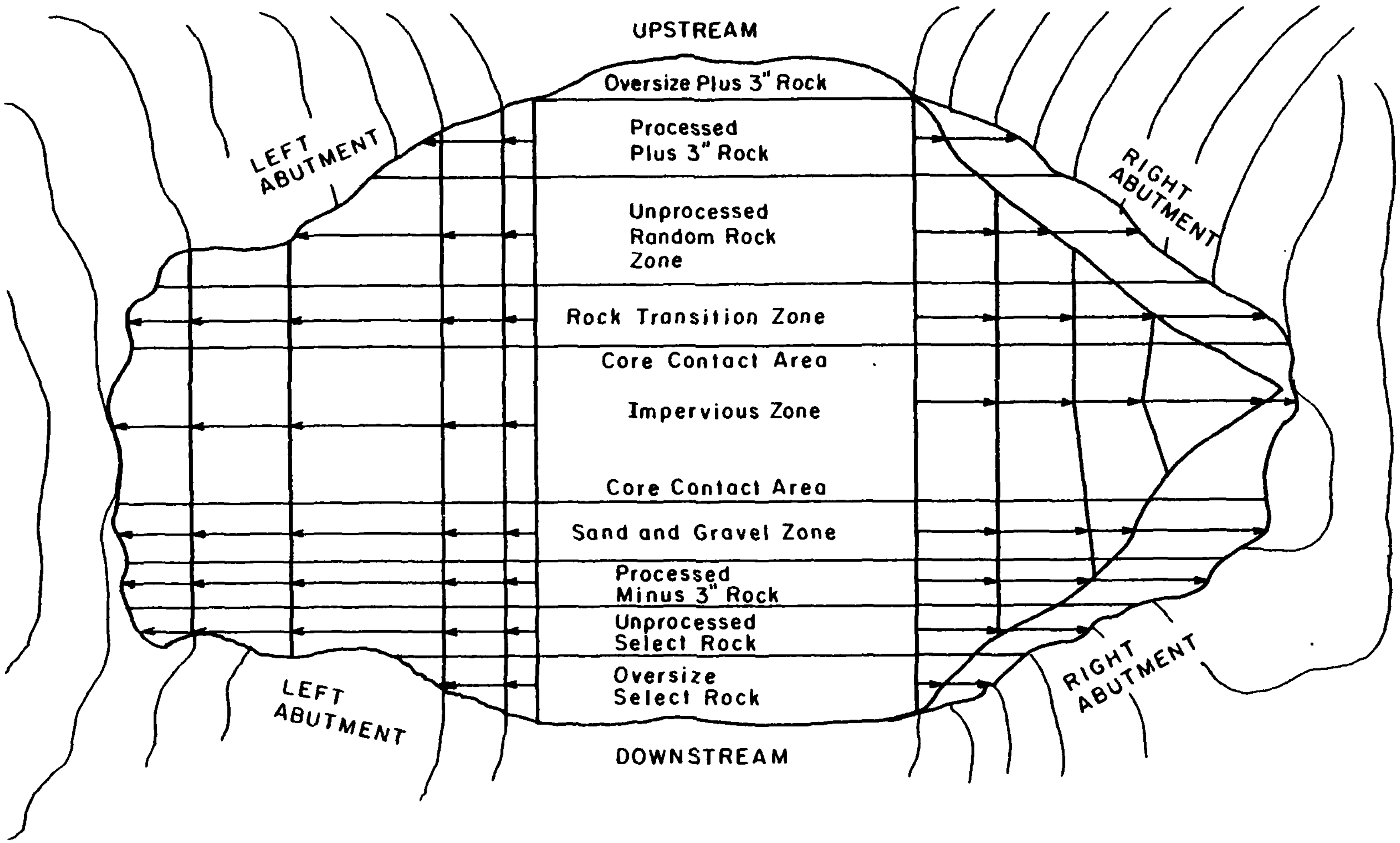


Figure 7. Schematic Plan View of Dam A

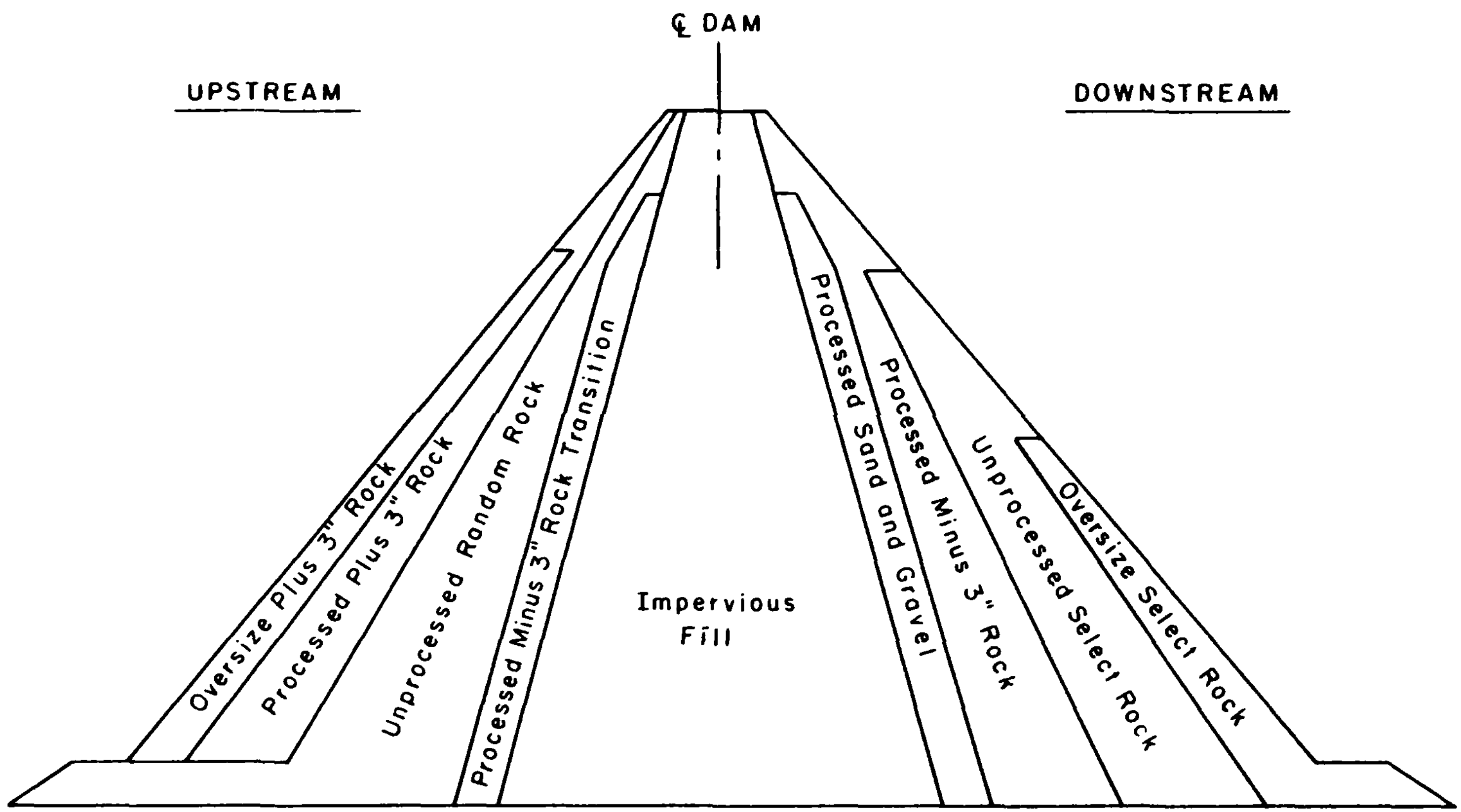


Figure 8. Typical Schematic Profile View of Dam A

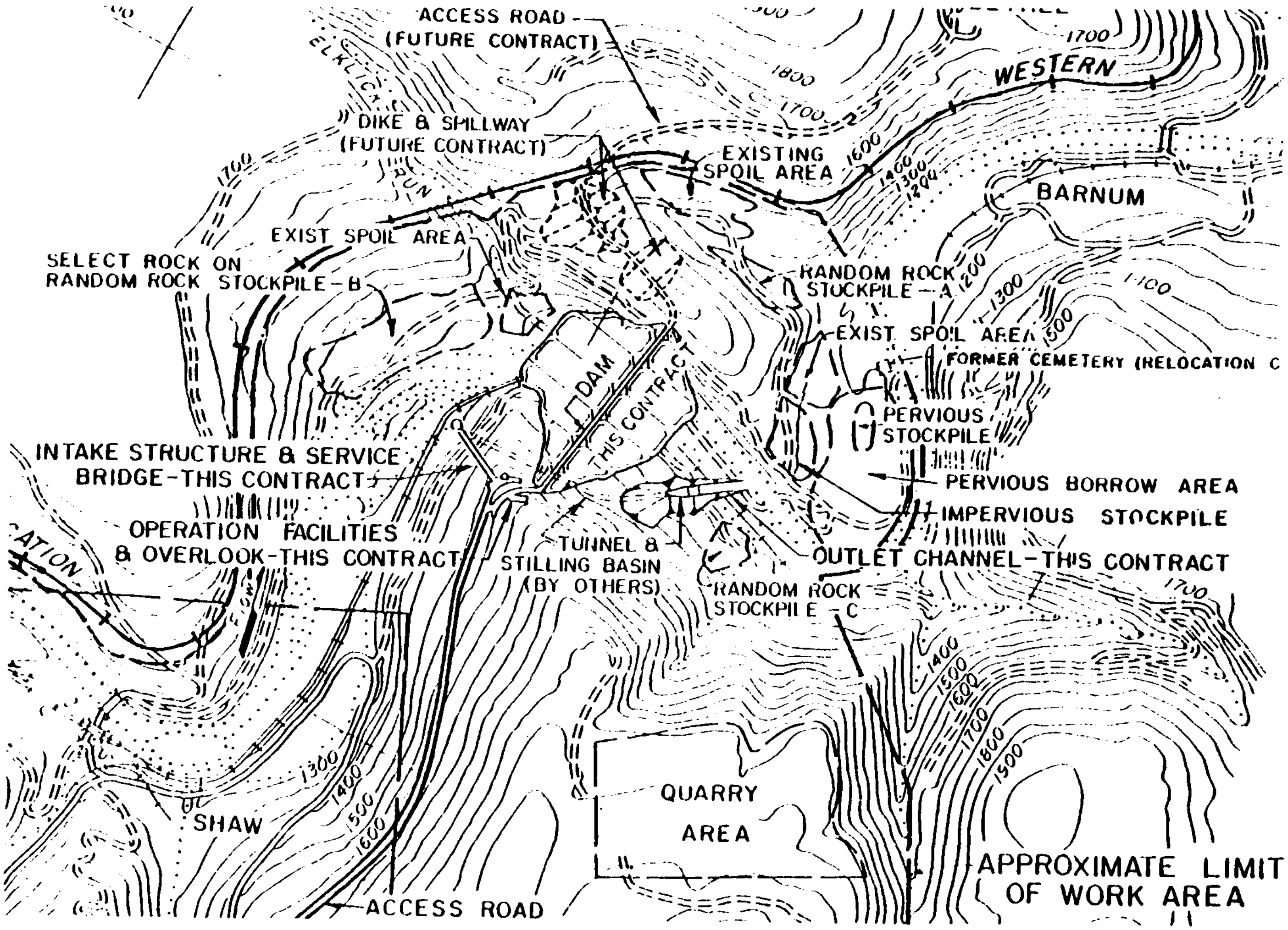


Figure 9. Dam A Borrow Area Location Map

(5 meters) tunnel 1,619 feet (493.5 meters) long. Two slide gates will control the flow through the tunnel. A rolled earth and rockfill dike, 900 feet (274 meters) long with a maximum height of 90 feet (27.4 meters) will be constructed across a low area on the left abutment. Construction of the main dam embankment began in late 1975 and is scheduled to be completed in the fall of 1980.

The critical core contact areas between the impervious zone (core) and both the upstream processed minus 3" rock transition zone and the downstream processed sand and gravel zones are noted in Figure 7. Figure 7 is a schematic plan view of a central area of Dam A. Other Dam A profiles at other stations along the dam are similar to the one shown in Figure 7. Figure 8 shows the primary zones of Dam A to be: 2" rock slope protection over the crest of the dam; processed plus 3" rock; unprocessed random rock; processed minus 3" rock transition; impervious zone; processed sand and gravel; processed minus 3" rock; unprocessed select rock; and oversize select rock.

Figure 9 is a map of the borrow areas and stockpiles used in Dam A. It should be noted that the borrow areas and stockpiles are widely dispersed around the dam. Controlling the flow of material from the correct borrow areas and/or stockpiles to the correct zones of the dam is therefore much more complicated than the earthmoving phase on an average highway project where fewer and less dispersed borrow areas must be controlled. This fact complicates the process control system which a contractor on a dam project must develop.

Dam A Operations. The dam and appurtances are being constructed by a general contractor utilizing the Quality Control Program Organization shown in Figure 10 and the currently used Corps of Engineers Contractor Quality Guidelines shown in Appendix B. The process of earthen dam construction begins with locating the dam site and selecting the borrow areas (both earthfill and rock quarry) based on laboratory tests. Each borrow area is evaluated for type of soil, variability of soil within a borrow area, Atterberg limits, liquid and plastic limits, shrinkage, compressibility, compactability, moisture content, and gradation. Additionally, studies are conducted to determine the economic feasibility of excavating and hauling borrow material and the environmental effect of removing the borrow material. Quarries are also evaluated to determine the type of rock, feasibility of removing rock, crusher location, methods of transporting crushed rock to the dam site, and the environmental impact of removing the rock from the quarry.

Testing Procedures and Facilities. Since soils exist in an enormous variety, and since the problems of applied soil mechanics also exist in a great variety, testing procedures for determining the engineering properties must not, in fact, cannot, be standardized. Before any soils testing is accomplished in the laboratory, the design engineer responsible for formulating the testing program must clearly define the purpose of each test.

It is generally necessary to adapt the testing procedure to the specific requirements of the investigation. For example, the consolidation test can be performed in various ways. What is often called the

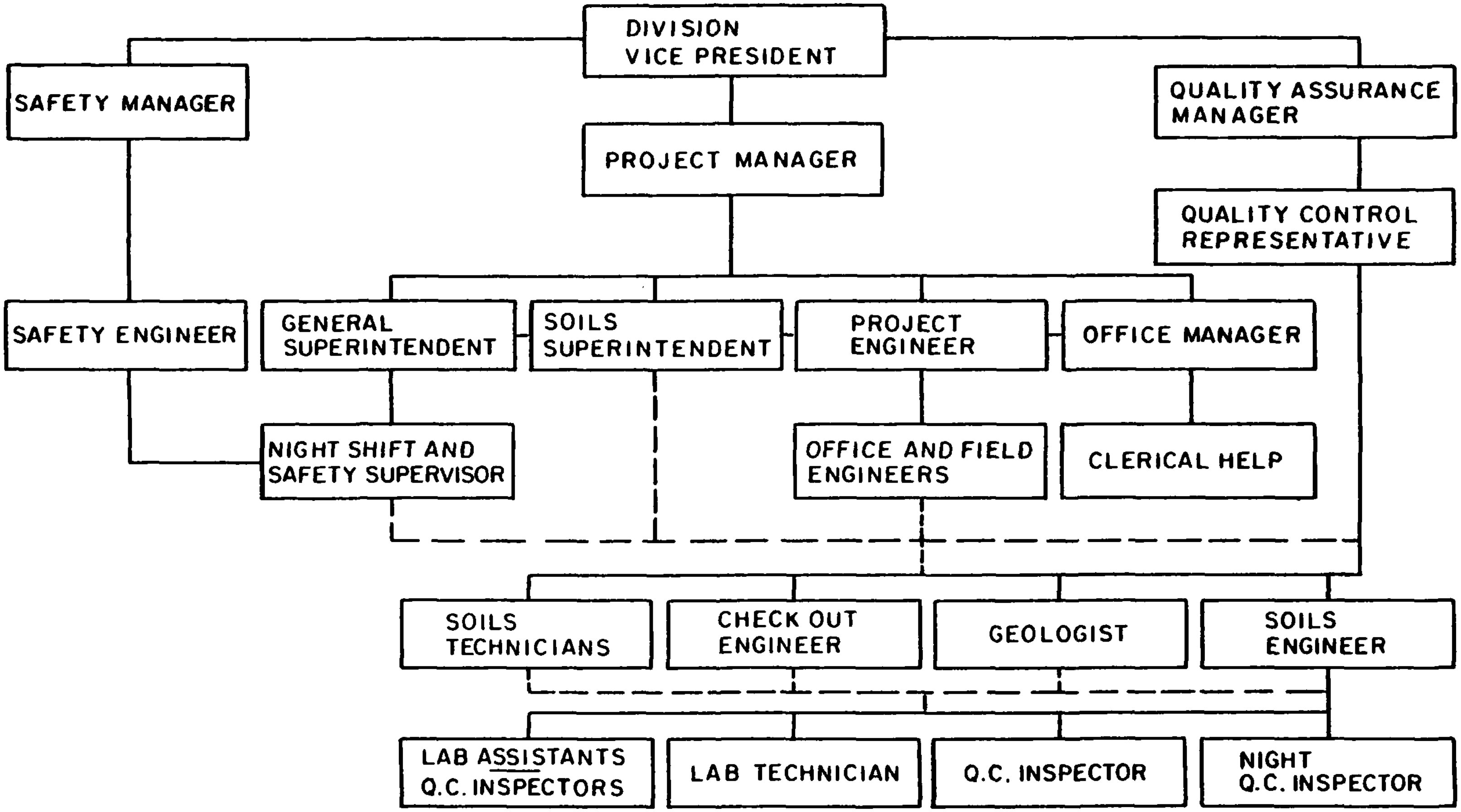


Figure 10. Contractor's Organization Chart on Dam A

"standard consolidation test" is performed by always doubling the previous load on the specimen. This procedure will produce time-consolidation curves that usually permit the most precise evaluation of the coefficients of permeability and consolidation. However, these load increments are not always satisfactory for defining the preconsolidation pressure curve from the shape of the void ratio-pressure curve; for this purpose, a much smaller factor than two should be used during incremental loading. The maximum load to which a consolidation test should be continued will depend on the consistency and stress history of the soil and the requirements of the project.

Tests which do not clearly measure defined engineering properties (such as Atterberg limits, specific gravity, grain-size analysis, and compaction) do require adherence to standardized procedures. Specific information regarding compaction controls and control procedures is contained in the abbreviated Corps of Engineers embankment specification presented in Appendix A. Compaction control is accomplished through the series of tests which is presented in Appendix A and the Corps' soils testing manual. Table 4 summarizes the existing required tests and the frequency of the tests in relation to the different embankment zones.

Procedures for soils tests necessary for the design of Corps projects appear as appendices to EM 1110-2-1906, "Laboratory Soils Testing," Office of the Chief of Engineers, Washington, D. C. The procedures are considered to represent the best current guidance for obtaining acceptable design data. Deviations from these procedures may be necessary on occasion, according to the judgment of the testing or design engineers, their experience with local soils, or peculiarities

TABLE 4

SUMMARY OF REQUIRED SPECIFICATION TESTS AND TESTING FREQUENCY
(see Appendix A for additional data)

Zone	Test	Frequency of Test
Impervious	Water content	Minimum of 1 per 5,000 CY in-place
	Atterberg limits	Minimum of 1 per 5,000 CY in-place
	Specific gravity	Minimum of 1 per 5,000 CY in-place
	Grain-size analysis	Minimum of 1 per 5,000 CY in-place
	Compaction	Minimum of 1 per 5,000 CY in-place
	Relative density	Minimum of 1 per 5,000 CY in-place
Minus 3-inch rock	Water content	Minimum of 3 tests at initial stage of processing each new blast, then minimum of 1 test per 25,000 CY in-place
	Grain-size analysis	Minimum of 3 tests at initial stage of processing each new blast, then minimum of 1 test per 5,000 CY processed
Minus 3-inch rock transition	Water content	Minimum of 3 tests at initial stage of processing each new blast, then minimum of 1 test per 5,000 CY in-place
	Grain-size analysis	Minimum of 3 tests at initial stage of processing each new blast, then minimum of 1 test per 5,000 CY processed
Processed gravel and processed sand and gravel	Atterberg limits	Minimum of 1 per 4,000 CY processed Minimum of 1 per 8,000 CY in-place
	Grain-size analysis	Minimum of 1 per 4,000 CY processed Minimum of 1 per 8,000 CY in-place
	Relative density	Minimum of 1 per 5,000 CY in-place
	Modified Providence Vibrated Density Test	Minimum of 3 tests total
Unprocessed rock fill	Grain-size analysis	Minimum of 20 tests

TABLE 4 (Continued)

Zone	Test	Frequency of Test
Plus 3-inch rock	Grain-size analysis	Minimum of 10 tests from processing plant Minimum of 10 tests from in-place material
Borrow areas	Water content Atterberg limits Porosity Degree of saturation Unit weight Shrinkage limit Specific gravity Grain-size analysis Compaction Permeability Consolidation Drained (S) direct shear test Drained (S) repeated shear test Triaxial compression Unconfined compression Relative density	All as needed to determine suitability; to classify soil and rock; establish in-place compaction criteria

of a project. Acceptable guidelines pertaining to testing equipment are also presented in the Corps' soils testing manual.

Compaction Controls and Control Procedures. The process of embankment compaction requires the contractor to: (1) furnish all plant labor and equipment; (2) perform all operations in connection with preparing the dam and spillway foundation; and (3) process, place, spread, and compact all permanent fills and backfills for the dam and spillway.

The results of the compaction tests are recorded daily on the standard Corps form, shown as Figure 11. Quality control reports are submitted on a daily basis by the contractor on a report form similar to the example shown at the end of Appendix B. Out-of-control limit results, or other quality control problems, are reported as they are discovered to the Corps Contracting Officer who is responsible for the overall conduct of the project. The Contracting Officer must then decide the appropriate course of action to be taken and issue a directive to the contractor's project superintendent which allows him to continue work or requires that corrective action must first be taken. Daily data forms are maintained by the contractor until the end of the month. They are then forwarded to the Contracting Officer. The Contracting Officer conducts periodic meetings (normally weekly) with the contractor to discuss problem areas and/or trends depicted by the test data or quality control reports. The data form provides a historical record of test data which is maintained by the Corps throughout the life of the dam. As such, it is of great value in determining causitive factors in cases of dam weakening or failure.

ENG FORM 4080 — SUMMARY OF FIELD COMPACTION CONTROL OF IMPERVIOUS OR SEMIPERVIOUS SOILS FOR CIVIL WORKS PROJECTS — RCS: ENGCW-E-11(R1)

Project	River / State / Town	Contract No	Contractor	Date of Report	Report No
Main Embankment Closure Section ___ Dam	(nearest)	(Fill in if desired for district or division use)		(date transmitted from field)	73 — Sheet 1 of 1

Embankment Zone	% Comp (S) Specified or (D) Desired	± % Limits	Compaction Equipment (S)	Loose Lift Thickness (In)	Number of Passes	Contact Pressure (PSI)
Upstream	95 D	+2 to -3 S	SFR	8	8	517
Central	95 D	+2 to -2 S	SFR	8	8	517
Downstream	95 D	+2 to -3 S	SFR	8	8	517

Test No	Date Placed	Type Test	Station	Offset (Ft)	Elevation (Ft)	Depth (In)	Embankment Zone	Borrow Source	Class Word or Letter Symbol	Max Part Size (In)	% Passing No 4 Sieve	% Passing No 200 Sieve	LL	PI (Not PL)	In-Place Total Sample Dry Density (PCF)	In-Place Total Sample Water Content (%)	In-Place -No 4 Fraction Dry Density (PCF)	In-Place -No 4 Fraction Water Content (%)	Lab Standard Method Test	Max Dry Density (PCF)	Opt Water Content (%)	Liquid Limit Correlation Max Dry Density (PCF)	Liquid Limit Correlation Opt Water Content (%)	W ± % Opt	Percent Compaction	Comments on Tests
Col 1	Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8	Col 9	Col 10	Col 11	Col 12	Col 13	Col 14	Col 15	Col 16	Col 17	Col 18	Col 19	Col 20	Col 21	Col 22	Col 23	Col 24	Col 25	Col 26	Col 27
488	1965 4 Mar	SV	147+50	480 DS	93	*	DS	*	SP	*	*	7	NP	NP	-	-	114.8	9.8	-	-	-	112.7	12.9	-3.1	102	
489	4 Mar	CYL	149+30	20 DS	104	*	Central	*	CH	*	*	62	52	32	-	-	110.0	16.5	-	-	-	107.2	17.1	-0.6	103	
490	4 Mar	CYL	149+00	175 US	105	*	US	*	CL	*	*	44	37	25	-	-	111.9	14.1	-	-	-	116.0	12.9	+1.2	96.5	
								Following data from	___				Dam,				District					Visual Class				
545	1963 9 Jul	NM	10+05	110 US	1375	*	A	Spillway Excav	CL(E)	*	*	*		*	113.0	*	-	-	-	-	-	113.5	*	-	98.8	
3	9 Jul	WV	10+05	110 US	1375	*	A	Spillway Excav	CL(E)	*	*	*	*	*	110.7	*	-		-	-	-	113.5	*	*	97.7	Check test on NM
								Following data from	___					Dam,			District					1 Pt. Std.				
CRF 7 DM D 30	1963 6 Sep	SV	7+25	85 DS	797	*	Random	Excav	SM	*	*	*	*	*	136.7	7.2	121.5	11.5	-		-	124.8	10.2	-3.0	97.3B	
CRF 8 DM D 48	9 Sep	SV	8+00	90 US	826		Impervious	Borrow	SM	*	*	*	*	*	126.2	9.6	118.9	11.9	-	-	-	126.3	10.2	-0.6	94.1B	
								Following data from	___					Dam			District									
404	1964 19 Ag	CYL	30+00	8 DS	705	*	Impervious Core	*	MH	*	68	27	75	34	82.3	34.6	68.4	44.4	(A)	84.0	37.0			+7.4	81	
707	21 Sep	CYL	20+00	℄	801		Impervious Core		MH		76	37	74	32	91.1	27.4	81.0	34.9	(A)	81.0					100	

* Information not given in field report but should have been.

ATTN: Compaction procedure using 12 in. mold was added to EM 1110 2 1906 after note on COL. 20 (see below) was prepared.

U.S. Army Engineer District, ___ Corps of Engineers

Prepared by: (Inspector)

Submitted by: Resident Engineer

Figure 11. Example Corps Data Form (13)

A problem with compaction control is directly associated with the length of time which is required for the various soil tests. Most of them take 24 hours or more to complete. The test results are therefore historical in nature and retard reaction to substandard test results. Within the time required to conduct the test(s), additional lifts may have been added above the tested lifts. A substandard test result therefore may require that the additional lift(s) be excavated so that the substandard lift may be reworked and retested. However, until less lengthy test methods, e.g., nuclear densometer, are either established or proven acceptable, this very real construction problem will continue. It should be noted that this problem, which exists whether present control procedures are used, or whether a more refined process control system is developed, is another source of complexity which must be considered.

Practical Applications of Control Chart Theory

Each dam has unique process control requirements. These requirements vary because of the difference in soil types, compaction equipment, personnel associated with each particular dam, and variances of zones particular to earthfill and rockfill dams.

An evaluation by the writer after the review of the above-mentioned factors, as well as others, resulted in a decision to develop a process control system for Dam A which incorporates control chart/ tabulation methods for only the impervious zone, while retaining the existing practices of control for all other embankment zones. One of the reasons is that the impervious zone (or core) is the most critical embankment zone in an earth and rockfill dam and therefore requires

the most testing and analysis. It is felt that control chart and tabulation techniques will provide a more effective evaluation of the compaction process used on the impervious zone than the existing practices of control.

Suggested Control Theory Procedures. As noted earlier, the process of embankment compaction begins with the retrieval of borrow material from borrow areas and/or quarries designated by the Contracting Officer. Each zone in the dam has specific soil or rock types and gradations from designated borrow areas and/or stockpiles. A single embankment zone such as the imprevious zone may, however, be serviced from different borrow areas or stockpiles. Therefore, the first step in the control process is ensuring that the correct borrow area or stockpile material is selected and transported to the proper area in the embankment. This appears to be a simple concept, but it is one that may be easily abused. One method which may be used to provide satisfactory control in this critical activity is the "batch ticket" concept, herein renamed the "embankment ticket." An embankment ticket could be issued from the Contracting Officer to the contractor designating the borrow area, soil or rock type, and area of placement on the dam. A Corps or contractor representative at the borrow area would verify, by initialing the embankment ticket, that the correct borrow area was being used. A representative at the dam zone placement site would also verify the embankment ticket by initialing. The embankment tickets would then be submitted to the soils engineer to be attached to the daily and monthly data reports. Substandard test results could then be better analyzed by eliminating questionable items related to soil type and borrow source.

A major problem associated with borrow areas at Dam A was noted during an interview between the writer and the Corps geologist at the dam site:

> Stratified soils cause particular problems in the Northeast United States. The stratified soil is a result of glacial action or weathering of rocks (residual soils) which left the soil in layers which may be alternatively good or poor for embankment materials. For this particular problem, special attention must be given to borrow areas almost constantly so that undesirable soils are not taken to the embankment. Soils personnel must be on site to divert unsatisfactory soils to dumping areas (1).

There are two crusher sites at Dam A which provide aggregate. The crushers can operate for a 24-hour period if the demand exists. The crushers are computer controlled and centrally monitored by television cameras. Process control for aggregate is not within the scope of this thesis and therefore will not be discussed further.

Sampling and testing plan

Every process control activity that includes sampling must have a pre-defined sampling and testing plan. Some activities have their sampling and testing frequency determined by the specification; other activities do not. These activities require a randomized sampling plan. This plan may be established by the soils engineer by using a time, planar, or volumetric basis. The choice of the basis depends on the process and the sampling and testing technique used.

Interrelated with sampling and testing frequency is the method which is used to subgroup test results. The subgrouping method determines, to a large extent, the type of information that the control chart is capable of providing. The importance of subgrouping

should not be overlooked. Different subgrouping techniques will create different control limits for the same process.

The subgroup size is equally important when dealing with data that is non-normal. As stated in Chapter 3, subgroups should be of size n greater than 1 whenever possible. If subgroups have been established by collecting samples at one point in time, it is the writer's opinion that subgroups of size n any larger than 2 would be impractical because of the time consuming test methods which are presently employed in soils testing, the limited number of soils laboratory personnel, and the cost of testing. If the subgrouping rationale were based on samples obtained over a period of time, subgroups of n any larger than 2 would be impractical because the identification of a problem in the compaction process would be delayed. This would decrease the value of the control chart. The choice of subgroup size should be based on both the method of subgrouping and the time and cost involved in sampling and testing the material characteristics.

The choice of sampling and testing frequency may well be an economic decision. The contractor and the Contracting Officer must weigh the costs associated with the sampling and testing frequency with the value obtained through the use of the resulting process control system in minimizing the rejection of a compacted area. This frequency is often limited by the available manpower, testing equipment, and quantity of material placed and compacted.

Documentation

Once the activities, testing frequencies, and subgroups have been established, the contractor and/or Contracting Officer must decide

on the type of types of control charts that are most valuable or practical for the process. Chapter 3 described three control chart techniques which are considered useful in controlling a process. The choice of which type of chart to use depends upon the subgrouping technique that is to be employed, the time and cost involved in obtaining the data, and the intended function of the control chart(s).

The most informative process control system would require the use of statistically based control charts for every possible control characteristic considered in the specification. Clearly, this would provide the maximum assurance of high quality compaction. However, this system would, as shown later in this chapter, involve the use of as many as 57 control charts for Dam A if the material for each zone is taken from only one of the acceptable borrow sources for that zone. The number of control charts required would increase if multiple borrow sources were used for the same zone. Obviously, this would impose an unreasonable burden on the laboratory technicians, who at this time may be unaware of the long range benefits of process control. Also, this system may well increase the cost of the project due to the contractor hiring more personnel to handle the additional workload (17).

By using the process control theory to manage only the impervious zone, the number of required control charts can be reduced significantly, as will be shown later in this chapter. The critical impervious zone compaction operation could then be evaluated more thoroughly with more assurance of satisfactory results.

An alternative approach to documentation is the partial use of a tabulation technique for monitoring less critical characteristics. Since the specification does not define the means for attaining process

control, it is the writer's contention that a contractor could develop a valuable impervious zone process control system by employing both control chart and tabulation techniques. While a contractor could conceivably fulfill the process control requirements by tabulation techniques alone (essentially by following the procedure presented in Figure 12), the effectiveness of such a system, in the writer's opinion, would be far below that of a proper mixture of techniques. The advantage of the control chart over a tabulation method is its ability to identify trends by providing a graphical display of the variation of the data.

Supportive data

Any control chart or tabulation technique which directly contains all the relevant information about the samples would become cumbersome. To supplement the information that is provided in a control chart or tabulation, detailed forms should be used which would allow supportive data to be recorded. These forms could than be used to investigate assignable causes of variation that are identified by out-of-control points. Any pertinent information that may be useful in tracing assignable causes should be included on the forms. The Corps of Engineers uses standard forms such as shown in Figure 11 which already contain the necessary information.

Selection of control limits

Before control charts can be beneficial, control limits must be established. Chapter 3 pointed out that control limits may be computed in either of two ways, depending upon the available information about

TABULATION OF ATTERBERG LIMITS DATA

Project: ______________________ Zone: ____________________

	UCL Target LCL				
Date (Day/ Month/ Year)	Test Number	Liquid Limit (LL)		Plasticity Index (PI)	
		X	R_2	X	R_2
____	____	____	____	____	____

NOTE: X - individual test data points
R_2 - range difference of two consecutive tests

Figure 12. Proposed Tabulation Data Form for Atterberg Limits of Impervious Zone of Dam A

the construction material characteristic being tested. If the population parameters $\overline{X}$ and σ' are known or assumed, the control limits may be calculated immediately. Compaction curves for each type of material will specify the maximum density. Compaction density limits are highly dependent upon the soil type, lift thickness, moisture content, and type of compaction equipment used. Therefore, the control parameters are interrelated and not readily distinguishable as entities by themselves.

Past and current data can be used effectively to determine the validity of specification limits and compaction methods. A trend showing values below the lower control limit (LCL) may indicate incorrect selection of control limits and/or incorrect compaction methods or compaction equipment.

The data must, however, have been collected for a similar type of material that is being used in the zone of the dam which is being examined. Duncan (11) points out that control limits should be calculated by computing the standard deviation of data that has been lumped together. Therefore, in order to use past data, it is necessary that it was sampled according to a logical subgrouping rationale. One problem with the use of appropriately sampled and subgrouped data is its inability to reflect any changes in the process that may have occurred subsequent to the collection of the data. For this reason, it is necessary to check those control limits with current process control data and revise them if necessary. Standard parameters, given in the specification and used to calculate control limits, should also be checked with current data. It is possible that

given standard parameters may not truly represent the specified process capability.

It is expected that laboratory test data will be used exclusively for implementing process controls. Samples for all process control activities should be randomly selected and a sufficient number of "historical data" samples should be selected before control limits are determined. The number of samples required will depend on the level of assurance which will be placed on the control limits. Therefore, increased confidence in the ability of the control limits to perform as intended requires a larger number of samples and a longer period of time for sampling and testing.

Control chart interpretation

Once control limits have been established, the interpretation criteria should be selected. This criteria should include at least two of the interpretation rules indicated in Chapter 3. One essential rule defines the "out-of-control" point criteria for three-sigma control limits. At least one extreme run rule should also be used in conjunction with this "out-of-control" point criteria. In most cases, the rule involving an extreme run of seven successive points on either side of the central line is sufficient. However, if these two simple rules prove to be inadequate in identifying lack of control, it may be necessary to employ additional rules for extreme runs.

Investigation of assignable causes

In order to fully utilize a control chart, a procedure should be developed for charting and analyzing results as rapidly as possible. Samples that are plotted and analyzed several days after they have been

taken may provide very little information in terms of day-to-day control. The intent of the process control system is to identify a problem while there is still time to correct it.

Included in the analysis of the control charts is the investigation made on characteristics which show lack of control. Care must be taken so that the responsibility for this investigation is placed on an individual who is not only familiar with the process, but who is also able to take the necessary time to see the investigation to a conclusion. A means for documenting the results of all investigational searches, including "dead-end" trails, should be established. Records of this nature will prove invaluable in identifying recurring problems.

System evaluation

Finally, the adequacy of the operating process control system should be evaluated by correlating both process control and acceptance results. It may be found that more or less frequent process control sampling and testing is required. It may also be found that certain control characteristics are unnecessary, or that additional control activities are required. Whatever the result, unnecessary or insufficient process control testing is costly and should be minimized.

Proposed Process Control System for Dam A. Process control responsibility should be assigned to someone experienced and familiar with the process system, normally the soils engineer. Since the writer had no means of performing the required laboratory tests for compaction, information and data were obtained from dam-related personnel including technicians, inspectors, geologists, surveyors, engineers, and superintendents. Information covering areas such as present means of

controlling compaction, areas where problems frequently occur, and corrective action taken for specific problems was obtained.

Process control activities

The dam embankment specification was reviewed to identify and establish the number of required process control activities as shown in Table 5. Standard tests and control limits are specified for each activity in the specifications and/or the Corps' soils testing manual. All of the testing activities have a minimum specified sampling and testing frequency (depending upon type of material and embankment zone as shown earlier in Table 4). If an $\overline{X}$ chart and range chart were developed for each characteristic, then a minimum of 114 charts would have to be provided. According to Dam A personnel, these activities represent standard activities which may not be economically adaptable to the statistical theory underlying the development of control charts. Some potential problems of utilizing statistical techniques which were noted are:

> Random selection of compaction testing points would be highly beneficial in order to remove the element of bias from the testing site selection process. However, the usefulness and economic benefit of the control chart technique for analyzing test data is questionable. The procedure is not feasible for a small dam project of less than $10 million due to the small staff employed for soils testing. Statistical techniques would either require the contractor to hire additional personnel, with resulting additional overhead cost and higher bid, or have the Corps personnel assume the additional statistical analysis requirements. However, large dam projects do have sufficient staff personnel to assume the additional requirements (17).

The criticality of immediately correcting substandard compacted areas is stressed in dam construction because of its vertical construction as opposed to the horizontal construction approach found in

TABLE 5

DESIRABLE PROCESS CONTROL ACTIVITIES
BASED ON AN INTERPRETATION OF THE
EXISTING EMBANKMENT SPECIFICATION
FOR DAM A

Process Control Activity	Number of Characteristics
Compaction	
Impervious zone	
Percent compaction	2
Relative density	1
Dry density	1
Moisture content	1
Liquid limit	1
Plasticity index	1
Specific gravity	3
Random earth zone	
Percent compaction	2
Relative density	1
Dry density	1
Moisture content	2
Unprocessed random rock and unprocessed select rock	
Moisture content	2
Processed pervious materials and transition material	
Moisture content	1
Percent compaction	2
Dry density	1
Relative density	1

TABLE 5 (Continued)

Process Control Activity	Number of Characteristics
Sieve analysis	
Impervious fill	2
Transition material	5
Processed gravel	5
Random earth	1
Unprocessed random rock	2
Unprocessed select rock	2
Processed pervious materials	
Processed gravel	5
Processed sand and gravel	7
Bedding material	5
TOTAL	57

highway construction. As noted earlier, in vertical placement, a substandard area must be reworked prior to placing the next lift. If the data are not quickly analyzed, the next lift may have been placed. The result may well require the removal of the last lift in order to recompact the substandard area, a process that would be costly both in time and economics.

Control charts have the advantage of providing a graphical display of the data which may be useful in identifying problems or trends. It is suggested by the writer that control charts be used wherever possible, particularly on the more important control characteristics such as moisture content and compaction characteristics (as will be discussed later). Less important control characteristics may be documented by tabulation methods. A combined control chart/tabulation process control system would provide useful information for the most critical zone of the dam--the impervious zone. Table 6 presents such a system, developed by the writer, of the process control charts which are felt to be necessary, based on a literal interpretation of the Dam A specification for the critical impervious zone. One example of a control characteristic is "the moisture content after compaction for the impervious zone shall be within the limits of 2 percentage points above optimum and 2 percentage points below optimum moisture content. . . ." It can be seen that if all the characteristics were to be controlled, there would be 6 control chart characteristics and 5 tabulation characteristics. The only real difference between existing process controls and statistical process control lies in the method used to obtain and evaluate the test results.

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TABLE 6

DESIRABLE CONTROL ACTIVITIES FOR
IMPERVIOUS ZONE OF DAM A:
CONDENSATION OF TABLE 5 ACTIVITIES

Process Control Activity		Number of Characteristics
A. Control Charts		
Compaction		
Percent compaction		1
Relative density		1
Dry density		1
Moisture content		1
Sieve analysis		2
	Control Chart Total	6
B. Tabulation Technique		
Liquid limit		1
Plasticity index		1
Specific gravity		3
	Tabulation Total	5

The proposed process control system is designed specifically for the impervious zone in order to provide the features of control charts to this critical zone. As seen in Table 7, existing Corps documentation and analysis of data methods will be used on the other embankment zones. It is the writer's opinion that the existing methods have been time proven and meet the standards required for these other embankment zones. For the impervious zone, however, it is felt that the added information which is gained seems well worth the additional work involved in actually plotting the control charts.

TABLE 7

PROPOSED DOCUMENTATION METHODS

Embankment Zone	Maintain Existing Methods of Documentation	Utilize Control Chart/ Tabulation Methods
Impervious		X
Random earth	X	
Unprocessed random earth and unprocessed select rock	X	
Processed pervious materials and transition materials	X	
Bedding material	X	

<u>Sampling and testing frequency</u>

It has been stated that the frequency of sampling and testing is related to three factors. The first factor is the available manpower and testing equipment. As pointed out earlier, this is dependent upon the size and scope of the project. However, this factor is practically

constant on the larger projects like Dam A (all receive similar manpower and testing equipment allocations). The sampling and testing frequency which is already defined in the embankment specification in conjunction with the impervious zone portion has been extracted and reassembled in Table 8. Such a requirement, for example, may note: "For the impervious fill, a minimum of one gradation test should be performed for each 5,000 cubic yards of material to be placed in the dam embankment and spillway fills unless otherwise directed by the Contracting Officer."

TABLE 8

PROPOSED PROCESS CONTROL TESTING FREQUENCY
SCHEDULE FOR DAM IMPERVIOUS ZONE

Characteristic	Frequency
Compaction	
Percent compaction	Minimum of 1 test per 5,000 CY
Relative density	Minimum of 1 test per 5,000 CY
Dry density	Minimum of 1 test per 5,000 CY
Moisture content	Minimum of 1 test per 5,000 CY
Sieve analysis	Minimum of 1 test per 5,000 CY

Before the specified frequency can be converted to a random basis, the varying amount of sampling and testing required for different materials and zones must be considered. For example, testing frequency of the critical impervious zone is greater than that for the transition zone. The development of a process control system for transition zone material, similar to the one proposed for the

impervious zone, would therefore merely involve an adjustment in the impervious zone sampling and testing frequency.

The third factor which affects the sampling and testing frequency is the method of grouping and size of subgroups. In most subgrouping methods, the larger subgroup sizes require more sampling and testing. This is particularly true when data represents samples that were taken, as nearly as possible, at one time. Schrock (32) and Duncan (11) pointed out that the object of subgrouping data is to minimize the chances of assignable cause occurring within the subgroup. It was felt that fewer chances for assignable causes to occur within a subgroup exist when samples are taken at one point in time. Since the estimate of the population standard deviation σ' is made from the average subgroup range $\overline{R}$, this subgrouping method is expected to provide the tightest set of control limits.

As noted earlier, from a practical standpoint, subgroups of $n = 1$ or $n = 2$ are necessitated due to the required length and cost of the test procedures. The choice of the subgroup size for each control activity is based on the cost and time involved in performing the test. Subgroups of size $n = 1$ should therefore normally be chosen. Subgroups of $n = 2$ may be selected to evaluate unusual areas.

<u>Randomization scheme</u>

As stated earlier, a random sampling plan may be developed on a time, planar, or volumetric basis. Sampling, as presented here, is based on a planar area one lift thick.

The following procedure is designed to provide data for establishing the statistical parameters pertaining to density, percent

compaction, and moisture content and related material characteristics. The testing is to be conducted on embankments as they are constructed under normal conditions and control methods. A lot will be defined as a portion of the project constructed in accordance with the specifications. The sampling unit will be a square yard of compacted material one lift thick.

Single samples should be taken or measurements made at random locations in the impervious zone. Each test lot should contain a minimum of 5,000 cubic yards of compacted embankment. A three-dimensional sampling plan, such as that shown in Figure 13, is recommended. The impervious zone should be divided into separate embankments, not necessarily of equal size, but large enough to contain at least 5,000 cubic yards each. The number of embankments to be sampled within the impervious zone is selected by multiplying the total number of embankment sections by consecutive random numbers from a random number table similar to the one shown in Table 9. The random numbers should be used as whole numbers and each product should be rounded off to the nearest whole number. The product gives the location in each embankment section where a test is to be taken.

The units in each embankment section to be sampled are determined in the following manner:

1. For each test section, start at any point in the random number table and select a consecutive group of three numbers, Z, X, and Y.
2. Multiply the first random number, Z, of each group by the maximum thickness or height, h, of each section at the centerline. This can be determined directly on the

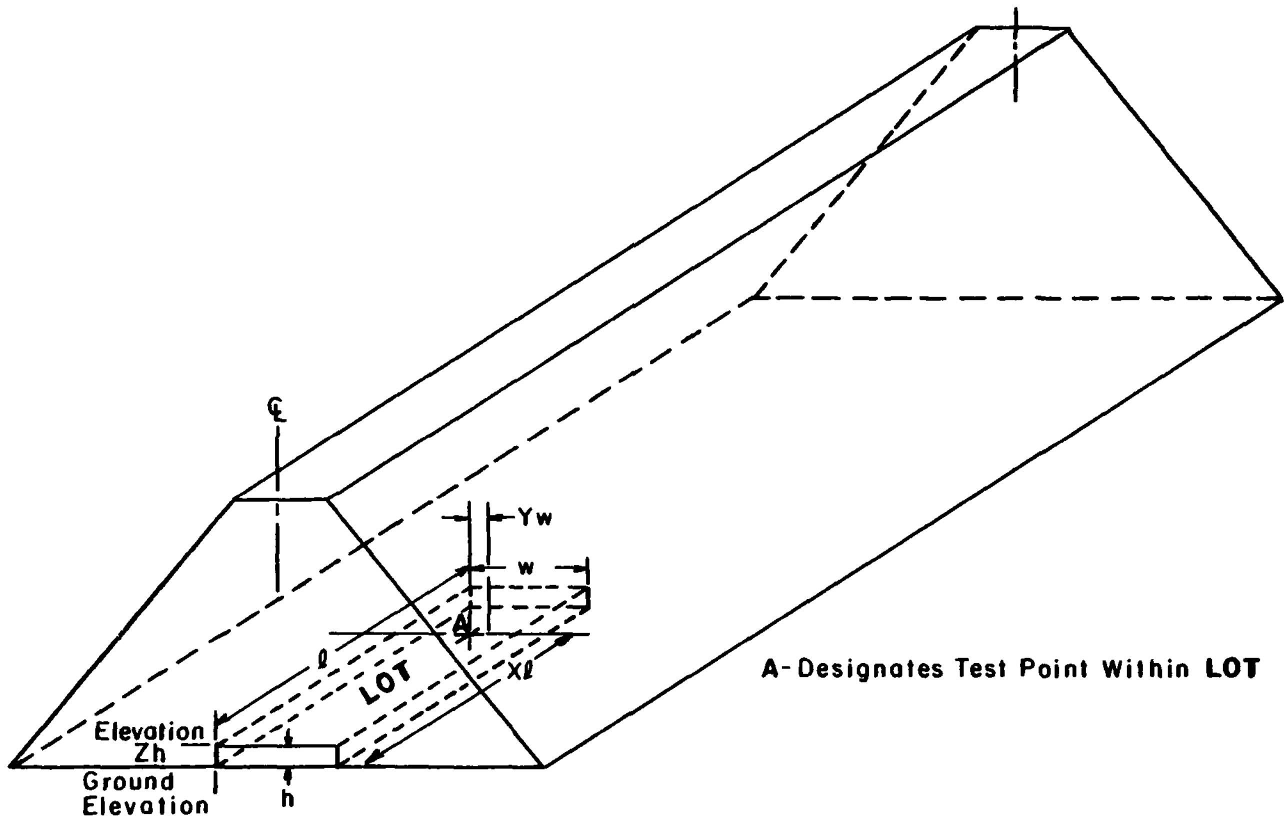

Figure 13. Parameters for Selection of Test Site by Randomization Scheme

TABLE 9

TABLE OF RANDOM NUMBERS (35)

.576	.730	.430	.754	.271	.870	.732	.721	.998	.239
.892	.948	.858	.025	.935	.114	.153	.508	.749	.291
.669	.726	.501	.402	.231	.505	.009	.420	.517	.858
.609	.482	.809	.140	.396	.025	.937	.310	.253	.761
.971	.824	.902	.470	.997	.392	.892	.957	.640	.463
.053	.899	.554	.627	.427	.760	.470	.040	.904	.993
.810	.159	.225	.163	.549	.405	.285	.542	.231	.919
.081	.277	.035	.039	.860	.507	.081	.538	.986	.501
.982	.468	.334	.921	.690	.806	.879	.414	.106	.031
.095	.801	.576	.417	.251	.884	.522	.235	.398	.222
.509	.025	.794	.850	.917	.887	.751	.608	.698	.683
.371	.059	.164	.838	.289	.169	.569	.977	.796	.996
.165	.996	.356	.375	.654	.979	.815	.592	.348	.743
.477	.535	.137	.155	.767	.187	.579	.787	.358	.595
.788	.101	.434	.638	.021	.894	.324	.871	.698	.539
.566	.815	.622	.548	.947	.169	.817	.472	.864	.466
.901	.342	.873	.964	.942	.985	.123	.086	.335	.212
.470	.682	.412	.064	.150	.962	.925	.355	.909	.019
.068	.242	.667	.356	.195	.313	.396	.460	.740	.247
.874	.420	.127	.284	.448	.215	.833	.652	.601	.326
.897	.877	.209	.862	.428	.117	.100	.259	.425	.284
.875	.969	.109	.843	.759	.239	.890	.317	.428	.802
.190	.696	.757	.283	.666	.491	.523	.665	.919	.146
.341	.688	.587	.908	.865	.333	.928	.404	.892	.696
.846	.355	.831	.218	.945	.364	.673	.305	.195	.887
.882	.227	.552	.077	.454	.731	.716	.265	.058	.075
.464	.658	.629	.269	.069	.998	.917	.217	.220	.659
.123	.791	.503	.447	.659	.463	.994	.307	.631	.422
.116	.120	.721	.137	.263	.176	.798	.879	.432	.391
.836	.206	.914	.574	.870	.390	.104	.755	.082	.939
.636	.195	.614	.486	.629	.663	.619	.007	.296	.456
.630	.673	.665	.666	.399	.592	.441	.649	.270	.612
.804	.112	.331	.606	.551	.928	.830	.841	.602	.183
.360	.193	.181	.399	.564	.772	.890	.062	.919	.875
.183	.651	.157	.150	.800	.875	.205	.446	.648	.685

profile or measured thickness of the placed material. The products, Zh, added to the ground elevation of the embankment base at the thickest or deepest part of the embankment will establish the elevation of the sampling plane.

3. Multiply the second random number, X, of each group by the length, ℓ, of the plane embankment section at the centerline. The resultant, $X\ell$, measured on the centerline from one end of the sampling plane, establishes the longitudinal position of a transverse line extending across the width of the embankment on the sampling plane. The test site will be located on this line at a point established by Yw (Step 4).

4. Multiply the third random number, Y, of each group by the width, w, of the sampling plane at the transverse line established in Step 3. The resultant length, Yw, measured from the embankment centerline, locates the test site on the transverse line determined in Step 3.

Density tests should be taken within the square-yard unit so located. Samples from the test holes should be split and each portion tested for moisture and any other characteristics of interest or specified.

It is suggested that the following calculations should be performed and recorded in the project records:

1. The percent of standard density, moisture content, and the values of other characteristics, if they are desired.

2. The historical mean, standard deviation, and the variance of the characteristics being tested that has been developed up until the lot in question was taken.

3. The relationships between the specified values and the measured values found in Step 2 above (35).

Documentation

Chapter 3 presented four control chart techniques: (1) control chart for individuals; (2) moving range chart; (3) trend indicator chart; and (4) Shewhart control charts. The Shewhart control chart technique requires test results to be grouped into subgroups of n greater than 1 which may not always be feasible for compaction testing.

It should be noted that only the control chart for individuals, control chart for dispersion, and trend indicator chart techniques are being suggested in Table 10. In order to keep the number of control charts within reasonable bounds, Table 11 suggests that a tabulation format be adopted for the desired control characteristics shown in Table 6. Table 10, therefore, contains the most important process control characteristics for Dam A in the most critical zone. It is felt that control charts do not have to be constructed for all types of soil testing because many of the tests are used only initially to classify the soil.

The characteristics which it is felt should be placed in a tabulation format are shown in Table 11. These characteristics were selected for tabulation because they are not controllable and control charts would therefore provide little benefit.

TABLE 10

SUGGESTED PROCESS CONTROL ACTIVITIES FOR THE IMPERVIOUS ZONE WHICH EMPLOYS CONTROL CHART TECHNIQUES[a,e]

Process Control Activity	Number of Characteristics	Types of Charts		No. of Charts
Compaction				
Percent Compaction	1	X^b, R^c, $\bar{X}_5{}^d$	(n=1)	3
Relative Density	1	X^b, R^c	(n=1)	2
Maximum Dry Density	1	X^b, R^c	(n=1)	2
Moisture Content	1	X^b, R^c, $\bar{X}_5{}^d$	(n=1)	
Sieve Analysis				
Gradation				
No. 4 Sieve	1	X^b, R^c	(n=1)	2
No. 200 Sieve	1	X^b, R^c	(n=1)	2
Total	6			14

[a]Assuming compaction of earth or sand-gravel materials under Corps Specification

[b]Chart of individuals identified as X

[c]R - difference of successive individual tests

[d]Trend indicator charts identified as X_i

[e]Other tests shown in Table 5 will follow present documentation requirements or the tabulation approach in Table 11

TABLE 11

PROPOSED PROCESS CONTROL ACTIVITIES EMPLOYING TABULATION TECHNIQUES[a,c]

Process Control Activity	No. of Characteristics	Type of Tabulation
Liquid limit	1	X, R,[b] (n = 1)
Plasticity Index	1	X, R,[b] (n = 1)
Specific Gravity	3	X, R,[b] (n = 1)
Total	5	

[a]Assuming dam compaction under Corps specification

[b]R - Difference of successive individual tests

[c]Tests conducted on compacted material

Each zone of the embankment is designated an authorized borrow source from which known soil type(s) will be excavated. Each soil type in each borrow source will have had the laboratory referenced testing performed in order to determine its parameters. The embankment ticket will show which borrow area was used as the source of embankment. The on-site tests will determine the in-place moisture content, maximum density, and relative density (as determined from in-place sand cone density tests and laboratory compaction tests. The test results must be recorded on the appropriate form for the particular borrow source and embankment zone.

The number of control charts required may vary from one dam to another due to their different characteristics. There is no method to establish the number of control charts required for a future project prior to development of the specification for the project.

The proposed documentation technique contains essentially the same information as presently tabulated (as shown in Figure 11). The proposed documentation methods will provide a contractor with a graphical display of the data in the form of control charts for the most important activities and a running average of tabulated data for the remaining activities.

Recording supportive data

Complete information regarding sampling and testing should be recorded to compliment any control chart or tabulation searches for assignable causes of variation. Figure 12 illustrated a proposed tabulation data form for Atterberg limits of the impervious zone of Dam A test data.

Control limits

Chapter 3 presented two possible methods for establishing control limits. One method required that the standard parameters $\overline{X}'$ and σ' be given or assumed. In effect, that is what is done when control limits are given for moisture content in the specification. Laboratory experiments conducted at the construction site by the U. S. Army Corps of Engineers determined these parameters for each soil type and embankment zone. These parameters can then be used to establish three-sigma control limits. As noted in Chapter 4, Grant and Leavenworth (18), three-sigma control limits usually provide the economic balance between false and late identification of trouble.

While the contractor is not directly required to collect data for the purpose of establishing his own control limits for these activities, it is the writer's opinion that this data should be collected to at least compare the contractor's compaction process capability to the stated standards. Schrock (32) substantiates this opinion by stating that standard control limits do not always show whether a particular process (such as specified for Dam A, for instance) is operating in a controlled manner at its natural level. They usually indicate divergence (whether controlled or not) from some standard. The standard may be too tight for one process and too loose for another. If the standards prove to be tighter than the contractor's compaction capability, then either a change in the contractor's fundamental process or a change in the standards is required to effectively utilize these limits. If the contractor's capability is tighter than the standard control limits, the control limits derived from the contractor's capability may be used to control the process.

Full control of a process is achieved by controlling both the central tendency ($\overline{X}$) and dispersion (R). When using only the standard control limits given in the specification for the moisture content, both controls may be used. However, for percent compaction, only control of the central tendency is possible. This arrangement provides reasonable control with minimum control chart effort if the process variability or dispersion for percent compaction remains in statistical control (18). It is the writer's opinion that this assumption should not be made without adequate evidence being obtained from each particular dam site. Consequently, data was collected for Dam A to establish conventional control charts ($\overline{X}$, R) for these process control activities. Since the standard control limits given in the specification are a contractural obligation, they must be employed. However, the three-sigma limits will be used to supplement them.

Summary

A general procedure, which may be used as a guideline for a contractor who must develop a statistical process control system for compaction of dam embankments, was presented in this chapter. The procedure has not been implemented on any known project. Both statistical control chart and tabulation techniques were recommended for use in this system in order to keep the number of control charts within a reasonable limit. Further, the statistical control system was limited to the most critical zone which is the impervious zone. A random sampling plan was presented which could be used to collect process control data for the purpose of computing control limits.

Chapter 5 presents the analysis of some actual data which was collected on Dam A. This analysis will provide an example of how the process control system developed in Chapter 4 can be implemented.

CHAPTER 5

ANALYSIS OF DATA

The previous chapter presented a procedure that could be used to develop a statistical process control system for the impervious zone of a dam. As indicated the system involves both control chart and tabulation techniques. Since each technique relies on the use of control limits, data was collected and evaluated to illustrate how these limits could be determined. The data for the impervious zone is presented in Appendix C.

It should be noted in Tables 16 and 17 that the test numbers do not start with test number 1. As noted earlier, test data were obtained for the tests conducted in April, May, and June 1979 during the current construction season. Data from previous construction seasons was not evaluated in order to remove as much variation from the test site selection and testing methods as possible. Inclement weather followed the evaluated period which caused numerous delays for extended periods in the embankment compaction. This resulted in intermittent testing which the writer feels is insufficient to produce conclusive results and was therefore not evaluated.

Tables 10 and 11 indicated that 6 sets of control charts and 5 sets of tabulations would be employed in order to present the complete process control system for the impervious zone. The minimum frequencies of the various tests was noted in the previous chapter. Because the test frequencies are based on the volume of fill compacted, there are no systematic testing frequencies. There is, therefore, no

logical subgrouping technique for multiple tests (n greater than 1). For the data that was available to the writer, subgroups of $n = 1$ (or single tests) appear to be the most logical for process control of the characteristics for both control charts and tabulation methods for the impervious zone of Dam A.

In this chapter, only several representative control charts and one tabulation based on subgroups of $n = 1$ are presented in order to illustrate the format and procedures which are involved in the technique. A control chart procedure will also be presented for a multiple subgrouping method ($n = 2$) to show a contractor how subgroups containing multiple tests might be analyzed if the test data had been collected to allow such a subgrouping arrangement.

Control Charts

It is the writer's belief that documentation of all of the process control activities listed in Table 10 would not overwhelm the unfamiliar contractor. Representative control chart analysis procedures will be shown for moisture content control ($\overline{X}$ and σ' known) and field dry density ($\overline{X}$ and σ' unknown). Control chart procedures for percent compaction, relative density, and sieve analysis would be similar to field dry density ($\overline{X}$ and σ' unknown). The documentation would probably follow the procedures outlined in the following section.

Moisture Content Control.

The materials in each lift must contain the amount of moisture specified in the contract specification (see Appendix A). The specification states: "The moisture content after compaction shall be within the limits of 2 percentage points above optimum and 2 percentage points below optimum moisture

content. . . ." Compacted cohesive soil that is placed at too dry a moisture content will undergo collapse when saturated under load. Conversely, cohesive soil placed too wet will not compact to the required density (39). For these reasons, the specification requires that "Material that is not within the specified limits after compaction must be reworked, regardless of density."

As noted in Chapter 2, for each compaction procedure, there is an "optimum" moisture content (OMC) which results in the greatest dry density for cohesive soils. At every other moisture content, both wet and dry of the "optimum," the resulting dry density is less than this maximum. It was also noted in Chapter 2 that, although most cohesive soils used in compacted fills have their own characteristic compaction curves, in some soils formed by the weathering of rocks in place (residual soils), the moisture-density curve for a given compactive effort is not unique but changes depending on the moisture content of the soil at the start of the test (39). This phenomenon appears to have occurred at Dam A. As can be seen in Table 17 (Appendix C), 17 different optimum moisture contents (resulting from 17 different moisture-density curves) were obtained for the impervious zone. The optimum moisture content occurs randomly. This randomness resulted in the various field moisture content tests being related to different optimum moisture contents.

This section will therefore provide a proposed control chart documentation procedure for moisture content control for the impervious zone for one of these optimum moisture contents, namely, 14.20 percent. A summary of the test results excerpted from Table 17 (Appendix C) which applied to soils with an optimum moisture content of 14.20

percent is presented in Table 12. Each moving range (R_2) is calculated as the difference between individual test results. Each trend indicator point ($\overline{X}_5$) is calculated as the average of five successive data points.

The control chart equations shown in Chapter 3 for $\overline{X}'$ known (optimum moisture content 14.20 percent) and σ' known (if it is assumed that $3\sigma' = 2$ percent above or below optimum moisture content; making $\sigma' = 2/3$) were applied as follows:

1. Chart of Individuals: $\overline{X}'$ and σ' known

   Central Line $= \overline{X}' = 14.20$ percent

   $UCL_X = \overline{X}' + 3\sigma' = 14.20 + 2.00 = 16.20$ percent

   $LCL_X = \overline{X}' - 3\sigma' = 14.20 - 2.00 = 12.20$ percent

2. Moving Range Chart of Two Consecutive Individual Observations: $\overline{X}'$ and σ' known

   Central Line $= d_2\sigma' = (1.128)(2/3) = 0.75$ percent

   $UCL_R = D_2\sigma' = (3.69)(2/3) = 2.46$ percent

   $LCL_R = D_1\sigma' = 0$ percent

   Note: $d_2 = 1.128$ (from Table 1; $n = 2$)

   $D_2 = 3.69$ (from Table 2; $n = 2$)

   $D_1 = 0$ (from Table 2; $n = 2$)

3. Trend Indicator Chart: $\overline{X}'$ and σ' known

   Central Line $= \overline{X}' = 14.20$ percent

   $$UCL_{\overline{X}_5} = \overline{X}' + \frac{3\sigma'}{\sqrt{kn}} = 14.20 + \frac{3(2/3)}{\sqrt{(5)(1)}} = 15.09 \text{ percent}$$

   $$LCL_{\overline{X}_5} = \overline{X}' - \frac{3\sigma'}{\sqrt{kn}} = 14.20 - \frac{3(2/3)}{\sqrt{(5)(1)}} = 13.31 \text{ percent}$$

   k = the number of observations or subgroups included in the moving average = 5

   n = 1 (for individual tests)

TABLE 12

TEST RESULTS OF IMPERVIOUS ZONE SOIL WITH OPTIMUM MOISTURE CONTENT 14.20 PERCENT[a]

Number of Tests	Date (Month/ Day) 1979	Test Number	Test Moisture Content X	R_2	$\bar{X}_5$
1	4/10	CPI-124	15.10		
2	4/10	CPI-128	13.10	2.00	
3	4/10	CPI-129	17.90	4.80	
4	4/10	CPI-130	17.40	0.50	
5	4/10	CPI-131	15.05	2.35	15.71
6	4/10	CPI-132	14.59	0.46	15.61
7	4/10	CPI-133	14.63	0.04	15.91
8	4/10	CPI-134	15.20	0.59	15.37
9	4/11	CPI-135	15.90	0.70	15.07
10	4/12	CPI-136	16.04	0.14	15.27
11	4/12	CPI-137	14.75	1.29	15.30
12	4/12	CPI-138	14.70	0.05	15.32
13	4/12	CPI-139	14.80	0.10	15.24
14	4/13	CPI-140	15.10	0.30	15.08
15	4/13	CPI-141	15.05	0.05	14.88
16	4/17	CPI-142	14.50	0.55	14.83
17	4/17	CPI-143	15.50	1.00	14.99
18	4/18	CPI-144	14.50	1.00	14.93
19	4/18	CPI-145	15.60	0.10	14.83
20	4/18	CPI-146	14.80	0.20	14.78

TABLE 12 (Continued)

Number of Tests	Date (Month/ Day) 1979	Test Number	Test Moisture Content X	R_2	$\bar{X}_5$
21	4/19	CPI-147	14.20	0.60	14.72
22	4/20	CPI-148	15.79	1.59	14.78
23	4/21	CPI-149	15.10	0.69	14.90
24	4/25	CPI-153	14.00	1.10	14.78
25	4/25	CPI-154	14.10	0.10	14.64
26	4/30	CPI-155	15.40	1.30	14.88
27	6/20	CPI-204	15.80	0.40	14.88

[a]Based on 27 tests (n = 1)

The resultant control charts: (1) the chart controlling the tendency (n = 1); (2) the range chart for controlling dispersion (n = 1); and (3) the trend indicator chart (n = 5) for identifying trends, presented in Figure 13, indicate the results of the data analysis for the optimum moisture content of 14.20 percent.

Based on the charts in Figure 14, control of moisture content appeared to be good. Two data points [noted on Figure 14 (a) as hollow circles] exceeded the upper control limit on the chart of individuals. Additional investigation indicate that these values resulted from moisture tests of stockpile material prior to placement and compaction. These values, in turn, affected the range chart values. The tests required no corrective action as they were pre-compaction tests. They are included in the control charts to illustrate out-of-control points to a contractor. If the out-of-control points had come from a compacted area, those areas would have had to be reworked and retested to verify that the data points would fall within the control limits.

As noted earlier, compacted cohesive soil which is placed too dry will more readily undergo collapse when saturated under load. This phenomenon does not occur with cohesive soils compacted at optimum water content or slightly wet of optimum. As seen in Figure 14 (a), the majority of data points lie between the optimum moisture content and the upper control limit, thus appearing to lessen the possibility of excessive settlement or collapse. This appears to indicate that the contractor's true average moisture content was above the laboratory targeted moisture content. In view of the fact that higher target moisture content was used by the contractor, perhaps a

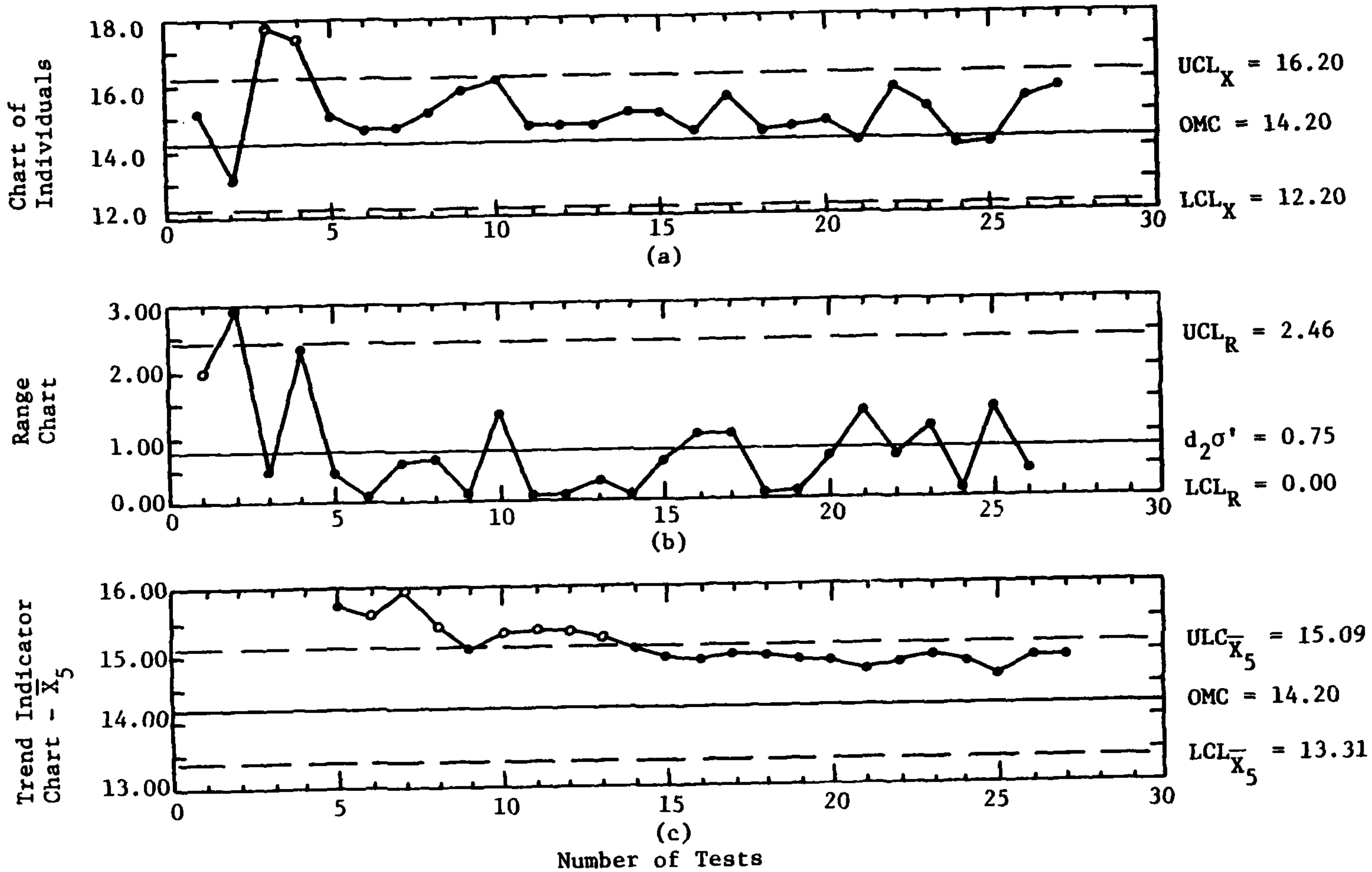

Figure 14. Moisture Content Control Charts
(Optimum Moisture Content - 14.20 Percent)

more appropriate control chart technique would be to use historical data to estimate the true $\overline{X}'$ and σ'. In order to insure process control, therefore, the central line and control limits should be revised based on the process control data. It appears that the revision would increase the target value and narrow the range of the control limits. The revised control charts would then provide more meaningful information on the process to the contractor. The practical construction implications of this were not researched in this thesis. This procedure, however, would closely parallel the case for dry density ($\overline{X}'$ and σ' unknown; $n = 1$) as discussed later.

An analysis of the moving range control chart indicates that the control is good. The control chart analysis of the trend indicator chart shown in Figure 14 (c) would normally suggest that the control limits had been incorrectly calculated. In this case, however, it indicates the construction practice above, where moisture contents were purposely kept between the optimum moisture content and the upper control limit. In addition, it should be noted that tests 5 through 8 are not indicators of lack of control because they include the data points for stockpile moisture tests, as mentioned earlier.

As noted earlier, an optimum moisture content of 14.20 percent was used to demonstrate the control chart procedure for moisture content control. A summary of all the moisture content results of the impervious zone of Dam A is presented in Table 13. These results are based on 72 tests of subgroup size $n = 1$ (as shown in Appendix C).

It should be noted that only 3 control charts were originally expected by the writer for moisture content control: (1) chart of individuals ($n = 1$); (2) moving range chart ($n = 1$); and (3) trend

TABLE 13

MOISTURE TEST RESULTS FOR IMPERVIOUS ZONE OF DAM A (PERCENT)[a]

Optimum Moisture Content (OMC)-$\overline{X}'$	Number of Tests	LCL_X	UCL_X	σ'	UCL_R[b]	$LCL_{\overline{X}_5}$[c]	$UCL_{\overline{X}_5}$[c]
13.00	12	11.00	15.00	0.67	2.46	12.11	13.89
13.10	4	11.10	15.10	0.67	2.46		
13.25	2	11.25	15.25	0.67	2.46		
14.10	3	12.10	16.10	0.67	2.46		
14.20	27	12.20	16.20	0.67	2.46	13.31	15.09
14.40	4	12.40	16.40	0.67	2.46		
14.50	1	12.50	16.50	0.67			
14.60	2	12.60	16.60	0.67	2.46		
15.00	1	13.00	17.00	0.67			
15.20	2	13.20	17.20	0.67	2.46		
15.30	1	13.30	17.30	0.67			
15.40	4	13.40	17.40	0.67	2.46		
15.50	1	13.50	17.50	0.67			
15.80	4	13.80	17.80	0.67	2.46		
16.20	1	14.20	18.20	0.67			
16.50	2	14.50	18.50	0.67	2.46		
18.00	1	16.00	20.00	0.67			

[a] Based on 72 tests ($n = 1$)

[b] UCL_R not applicable for single tests

[c] Number of tests insufficient at some optimum moisture contents to calculate $\overline{X}_5$

indicator chart (n = 5) at a single optimum moisture content for the impervious zone. In reality, as shown in Table 13, the writer found that the contractor is apparently faced with plotting $17 \times 3 = 51$ charts if he is to properly consider all of the different target moisture contents. This quantity of documentation would overburden the contractor.

One of the possible approaches to reduce the number of required control charts is to plot the difference of actual moisture content and targeted optimum moisture content. Another possible approach to reduce the number of required control charts is to plot the ratio of actual moisture content to the targeted optimum moisture content. In each of these approaches, all of the available data could then be plotted on the same control charts. The historical data could be used to estimate the values of $\overline{X}'$ and σ' of the difference or the ratio. The implications behind each of those methods were not researched in this thesis. Further research would be needed to evaluate their feasibility and effectiveness.

Dry Density and Percent Compaction Control. Moisture-density tests can be represented by the moisture-density curves which were illustrated in Figures 1 and 2. The ordinate of the peak of these curves is designated the maximum dry density, or 100 percent compaction, and the abscissa is the optimum moisture content. The field process control procedure initially consists of determining the moisture-density curve for each variant of the material and of performing tests to determine whether the placement moisture content is within the specified range and that the required dry density (or percent compaction) has been achieved. As noted in the previous section, in soils resulting from

weathering of rocks, tests may be needed to establish the identity of the materials and the optimum moisture content. Establishment of maximum dry density and percent compaction is therefore directly related to the optimum moisture content.

The discussion below has been divided into two parts related to individual dry density tests (n = 1) and combined dry density tests (n = 2) for optimum moisture content 14.20 percent. A proposed process control procedure will be established for each to illustrate the subgrouping technique options the contractor should use for the impervious zone. The individual dry density process control procedure uses the individual (n = 1) tests that are shown in Table 17 of Appendix C. The combined field dry density (or percent compaction) process control procedure mathematically combines two consecutive individual tests (n = 2) shown later in Table 15.

<u>Individual field dry density</u>

The individual field dry density tests results are shown in Table 14 for subgroup size $n = 1$. Each moving range (R_2) is the difference between individual test results. Each trend indicator point ($\overline{X}_5$) is the average of five successive data points.

The moisture-density curve defines the maximum dry density, or 100 percent compaction, for each test. The Corps' soils testing manual requires that the minimum dry density, or percent compaction, is 98 percent of its optimum compaction value established by the moisture-density curve. Since $\overline{X}'$ and σ' are not given, they must be estimated from the data in Table 14 by using the appropriate equations given in Chapter 3, as follows:

TABLE 14

INDIVIDUAL FIELD DRY DENSITY TEST RESULTS FOR IMPERVIOUS ZONE OF DAM A (lb/ft^3)[a,b]

Number of Tests	Date (Month/Day) 1979	Test Number	Test Field Dry Density[c]	R_2[c]	$\bar{X}_5$[c]
1	4/10	CPI-124			
2	4/10	CPI-127			
3	4/10	CPI-128			
4	4/10	CPI-129			
5	4/10	CPI-130			
6	4/10	CPI-131	116.14		
7	4/10	CPI-132	114.41	1.73	
8	4/10	CPI-133	118.86	4.45	
9	4/10	CPI-134	115.42	3.44	
10	4/11	CPI-135	112.19	3.23	115.40
11	4/12	CPI-136	114.18	1.99	115.01
12	4/12	CPI-138	115.57	1.39	115.24
13	4/12	CPI-139	116.75	1.18	114.82
14	4/13	CPI-140	113.68	3.07	114.47
15	4/13	CPI-141	115.97	2.29	115.23
16	4/17	CPI-142			
17	4/17	CPI-143	117.93	1.96	115.98
18	4/18	CPI-144	117.77	0.16	115.82
19	4/18	CPI-145			
20	4/18	CPI-146			

TABLE 14 (Continued)

Number of Tests	Date (Month/ Day) 1979	Test Number	Test Field Dry Density[c]	R_2[c]	$\overline{X}_5$[c]
21	4/14	CPI-147	111.17	0.60	115.30
22	4/20	CPI-148	112.38	1.21	115.04
23	4/21	CPI-149	115.03	2.65	114.86
24	4/25	CPI-153	116.86	1.83	114.64
25	4/25	CPI-154	112.69	4.17	113.63
26	4/30	CPI-155			
27	6/20	CPI-204			

[a]Based on 17 tests (n = 1); see notes regarding deleted tests in following notes

[b]Dry density results at optimum moisture content 14.20 percent

[c]Tests CPI-124, 127, 128, 129, 130, 142, 145, and 146 deleted (stockpile or trench moisture tests only)

Test CPI-204 deleted in computing R_2 and $\overline{X}_5$ (too much time elapsed from other tests to be compared)

1. <u>Chart of Individuals: $\overline{X}'$ and σ' unknown</u>

$$\text{Central Line} = \overline{X}_1 = \frac{\sum_{i=1}^{n} X_i}{n} = \frac{\sum_{i=1}^{17} X_i}{17}$$

$$= \frac{1957.00}{17} = 115.12 \text{ lb/ft}^3$$

$$\overline{R}_2 = \frac{\sum_{i=1}^{n-1} R_2}{n-1} = \frac{35.25}{16} = 2.20 \text{ lb/ft}^3$$

$$UCL_X = \overline{X}_1 + \frac{3\overline{R}_2}{d_2} = \overline{X}_1 + 2.66\ \overline{R}_2 = 115.12 + 2.66\ (2.20)$$

$$= 120.97 \text{ lb/ft}^3$$

$$LCL_X = \overline{X}_1 - \frac{3\overline{R}_2}{d_2} = \overline{X}_1 - 2.66\ \overline{R}_2 = 115.12 - 2.66\ (2.20)$$

$$= 109.27 \text{ lb/ft}^3$$

Note: $d_2 = 1.128$ (from Table 1; $n = 2$)

2. <u>Moving Range Chart of Two Consecutive Observations: $\overline{X}'$ and σ' unknown</u>

$$\text{Central Line} = \overline{R}_2 = 2.20 \text{ lb/ft}^3$$

$$UCL_R = D_4\ \overline{R}_2 = 3.27\ (2.20) = 7.19 \text{ lb/ft}^3$$

$$LCL_R = D_3\ \overline{R}_2 = 0\ (2.20) = 0 \text{ lb/ft}^3$$

Note: $D_4 = 3.27$ (from Table 3; $n = 2$)

$D_3 = 0$ (from Table 3, $n = 2$)

3. <u>Trend Indicator Chart: $\overline{X}'$ and σ' unknown</u>

$$\text{Central Line} = \overline{X}_1 = 115.12 \text{ lb/ft}^3$$

$$UCL_{\overline{X}_5} = \overline{X}_1 + \frac{3\overline{R}_2}{d_2\sqrt{kn}} = 115.12 + \frac{3(2.20)}{(1.128)\sqrt{(5)(1)}}$$

$$= 117.74 \text{ lb/ft}^3$$

$$LCL_{\overline{X}_5} = \overline{X}_1 - \frac{3\overline{R}_2}{d_2\sqrt{kn}} = 115.12 - \frac{3(2.20)}{(1.128)\sqrt{(5)(1)}}$$

$$= 112.50 \text{ lb/ft}^3$$

Note: d_2 = 1.128 (from Table 1; n = 2)

k = 5 (number of individual observations in moving average)

n = 1 (subgroup size for individual observations)

Figure 15 indicates the results of the data analysis for the individual field dry densities at optimum moisture content 14.20 percent. Three types of control charts have been illustrated: (1) the chart for controlling the central tendency (n = 1); (2) the range chart for controlling the dispersion (n = 1); and (3) the trend indicator chart (n = 5) for identifying trends. The control charts in Figure 15 represent the historical data phase. The additional data which the contractor would collect after the control chart was developed would be plotted as part of his ongoing process control activity. Since the primary purpose of presenting the control chart in this thesis is to provide an illustration of the technique which is used, more data would have to be collected in order to make it an operating control chart. It should be noted that the number of field dry density control charts would increase by 3 × number of individual optimum moisture contents, as discussed earlier.

Control appears to be fairly good on the chart of individuals and the range charts. All points are within the control limits. This may be a result of using only historical data to determine the central line and the control limits. Additional observations of the chart of individuals show that the data points are fairly evenly distributed

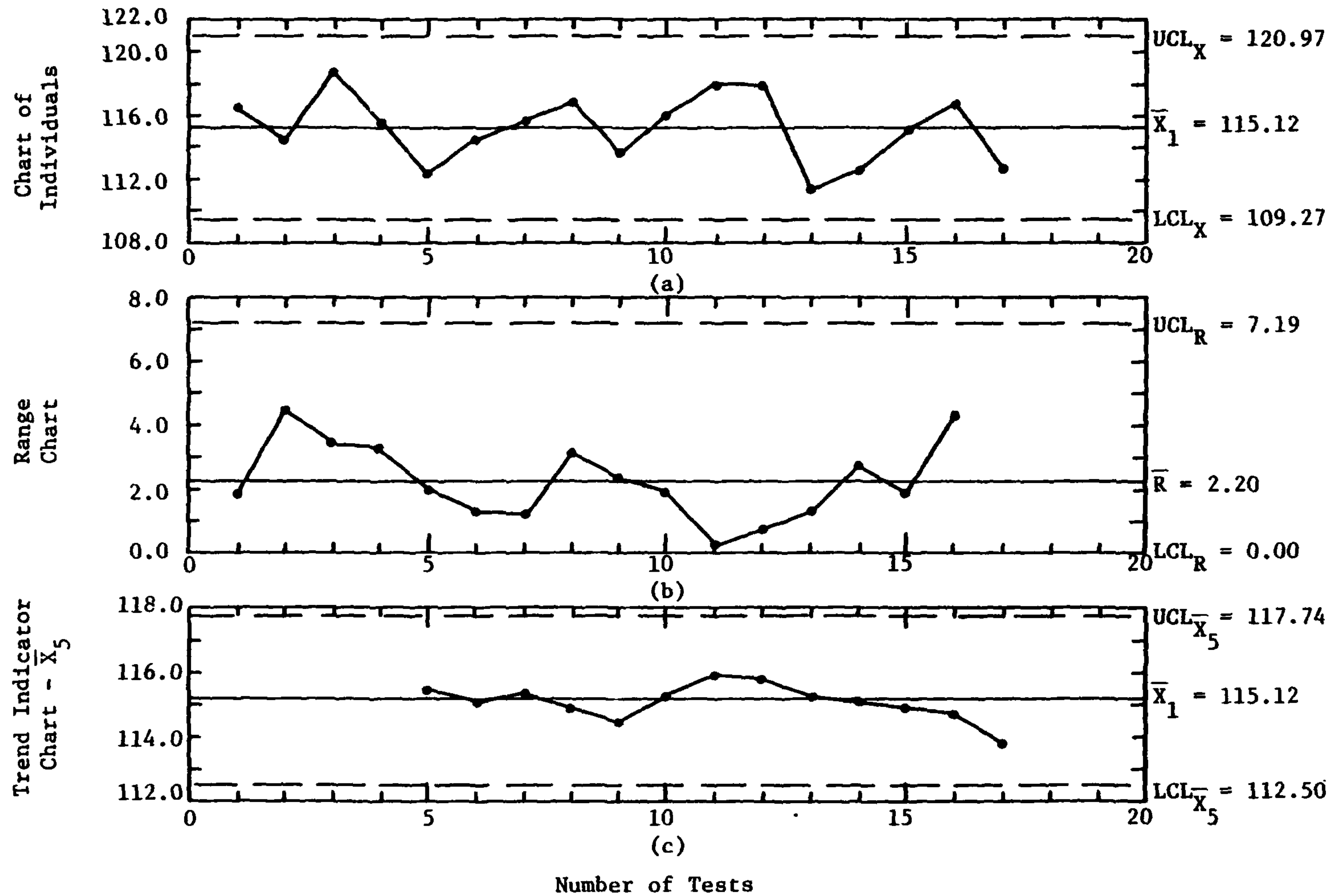

Figure 15. Individual Field Dry Density Control Charts for Impervious Zone of Dam A (lb/ft^3) (at optimum moisture control content 14.20 percent)

on both sides of the central line ($\overline{X}_1$). This may indicate that the $\overline{X}_1$ of the data was the best estimate of the process average.

The trend indicator chart plotted a moving average of five successive tests. Cycling is more apparent in the trend indicator chart because of the smoothing effect which has taken place. The contractor would have to determine the cause of the cycling as it occurs in order to correct the underlying problem.

It should be noted from Table 10 that percent compaction and relative density are also process control chart activities. Control chart procedures for these tests would follow the same basic procedures as for individual field dry density tests. It is recognized by the writer that percent compaction is used as the acceptance criteria rather than maximum field dry density. Field dry density was selected to illustrate this procedure, however, so that the contractor would see the importance of maintaining control charts for reasons other than acceptance criteria. The contractor should maintain charts for field dry density tests, percent compaction tests, and relative density tests concurrently to insure specifications are met and the critical impervious zone is safe and functional.

<u>Combined field dry density</u>

Combined field dry density will be used to illustrate a technique of grouping test results for Shewhart control charts. The actual practices used on Dam A indicates that there was not a logical grouping method used for the individual test results. As seen in Table 14, the number of tests varied from 1 to 9 per day. For illustration purposes only, each two consecutive tests will be arithmetically combined as a

grouping technique of $n = 2$. The results of such a procedure are shown in Table 15.

The control limit calculations, based on the Shewhart equations given in Chapter 3, are as follows:

1. <u>$\overline{X}$-Chart: $\overline{X}'$ and σ' unknown</u>

   $$\text{Central Line} = \overline{\overline{X}} = 115.27 \text{ lb/ft}^3$$

   $$UCL_{\overline{X}} = \overline{\overline{X}} + A_2\overline{R} = 115.27 + 1.88\ (1.73) = 118.52 \text{ lb/ft}^3$$

   $$LCL_{\overline{X}} = \overline{\overline{X}} - A_2\overline{R} = 115.27 - 1.88\ (1.73) = 112.02 \text{ lb/ft}^3$$

   Note: $A_2 = 1.88$ (from Table 3; $n = 2$)

2. <u>R-Chart: $\overline{X}'$ and σ' unknown</u>

   $$\text{Central Line} = \overline{R} = 1.73 \text{ lb/ft}^3$$

   $$UCL_R = D_4\overline{R} = 3.27\ (1.73) = 5.66 \text{ lb/ft}^3$$

   $$LCL_R = D_3\overline{R} = 0 \text{ lb/ft}^3$$

   Note: $D_4 = 3.27$ (from Table 3; $n = 2$)

   $D_3 = 0$ (from Table 3; $n = 2$)

Figure 16 shows the results of the data analysis for the combined field dry densities at optimum moisture content 14.20 percent. Two types of Shewhart control charts are shown: (1) the chart for control of the central tendency ($n = 2$); and (2) the chart for controlling process dispersion ($n = 2$).

The combined field dry density control charts shown in Figure 16 have too few data points to provide a thorough analysis of the data. As pointed out earlier, the test data was restricted to the early 1979 construction season. Once the central tendency and the control limits have been established using historical data, the additional process control data can be plotted on the control chart. At some later date, if it appears that the original central tendency and control limits do

TABLE 15

COMBINED FIELD DRY DENSITY RESULTS FOR IMPERVIOUS ZONE OF DAM A (lb/ft^3)

Subgroup Number	Test X_1	X_2	$\overline{X}$	R
1	116.14	114.41	115.28	1.73
2	118.86	115.42	117.14	3.44
3	112.19	114.18	113.19	1.99
4	115.57	116.75	116.16	1.18
5	113.68	115.97	114.83	2.29
6	117.93	117.77	117.85	0.16
7	111.17	112.38	111.78	1.21
8	115.03	116.86	115.95	1.83

$$\overline{\overline{X}} = \frac{\sum_{i=1}^{m=8} \overline{X}_1}{m} = \frac{921.95}{8} = 115.27\ lb/ft^3$$

$$\overline{R} = \frac{\sum_{i=1}^{m=8} R}{m} = \frac{13.83}{8} = 1.73\ lb/ft^3$$

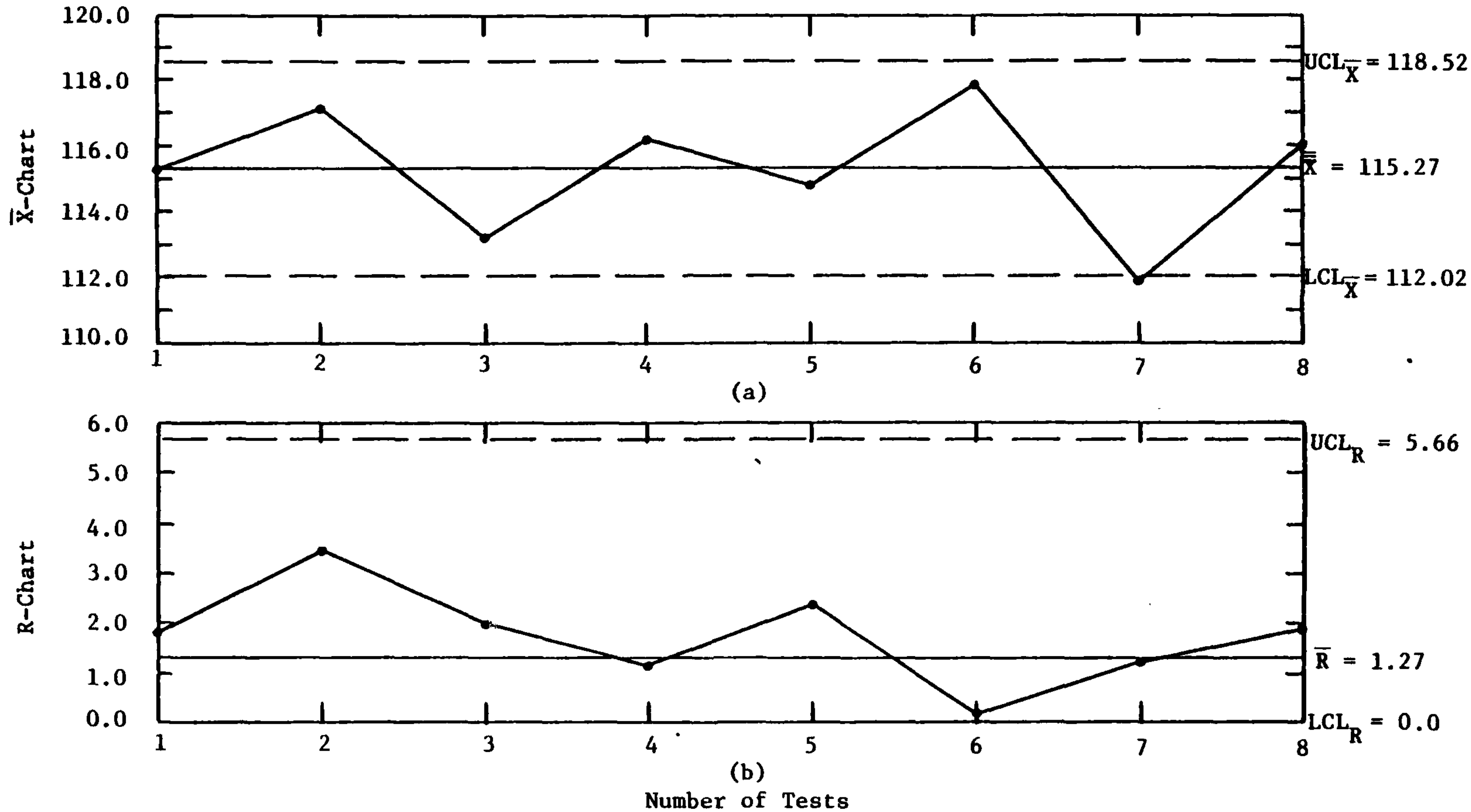

Figure 16. Combined Field Dry Density Control Charts for Impervious Zone of Dam A (lb/ft^3) (at optimum moisture content 14.20 percent)

not accurately represent the actual process, the limits can again be revised. The contractor would then use the revised control chart to plot his additional process control data.

Each value on the $\overline{X}$-chart in Figure 16 is the average of two consecutive field dry densities. Each value on the R-chart is the difference between those average densities. Good control of the central tendency and variation of the dry density results (n = 2) is shown on the control charts, as it should, since the central line and control limits were determined from historical data. The $\overline{X}$-chart shows that the points are fairly evenly distributed on both sides of the central line with no obvious recurring cycles, indicating that the $\overline{\overline{X}}$ of the data may be the best estimate of the process average. The R-chart shows no significant variation of test points. It should be noted that the test results were arithmetically combined (n = 2) by the writer for the purpose of illustrating the calculation technique. The writer had no valid basis for performing such a subgroup combination on the Dam A construction project. In an actual situation, the contractor must, of course, use a logical basis for subgrouping. The size of the subgrouping and related economic considerations are, in the writer's opinion, topics that would require future research.

Shewhart control chart procedures for combined percent compaction tests would follow the same outline as for combined field dry density tests. If the contractor would choose to use the combined field dry density procedures, he should also use the combined percent compaction control charts.

It should be noted from Figures 15 and 16 that the Shewhart control technique (combined field dry densities with n = 2) provides

a narrower control range (chart of individuals in Figure 15 versus $\overline{X}$-chart in Figure 16) and lower upper control limit for control of dispersion. The central line for both the individual and combined techniques is approximately equal (115.12 versus 115.27 lb/ft^3). However, the combined (n = 2) technique provides a much smaller average range ($\overline{R}_2$) than the individual technique (n = 1). The reason for this is the concept of the sampling distribution of means. As n gets largei, $\sigma_X = \frac{\sigma'}{\sqrt{n}}$ gets smaller, thereby providing the smaller range for $n = 2$.

It should be noted that when $n = 2$ is used, control limits which are calculated are not the same as the required control limits that the specification would indicate for the $n = 1$ condition. The practical construction implications of this fact were not researched in this thesis.

Tabulation Techniques

According to the proposed process control system presented in Table 11, the Atterberg limits and specific gravities are to be documented in a tabular format (n = 1). In order to facilitate the investigation of assignable causes, control limits for the central tendency and for the range are established for each characteristic. Atterberg limit data will be used to illustrate the proposed tabulation technique.

The Atterberg limits (liquid limit and plasticity index) test results for the impervious zone of Dam A are presented in Table 16. since $\overline{X}'$ and σ' are not known, the following calculations will be used to determine these values needed to establish the control limits.

TABLE 16

TABULATION OF ATTERBERG LIMITS DATA[a]

Project: Dam A Zone: Impervious

	LL X	LL R_2	PI X	PI R_2
UCL	41.3	10.8	18.6	7.5
Target	32.5	3.3	12.5	2.3
LCL	23.7	0.0	6.4	0.0

Date (Day/Month/Year)	Test Number	Liquid Limit (LL) X	Liquid Limit (LL) R_2	Plasticity Index (PI) X	Plasticity Index (PI) R_2
4/10/79	CPI-127	31.90	2.20	14.70	1.30
4/10/79	CPI-131	34.10	3.40	13.40	2.30
4/10/79	CPI-132	37.50	4.30	15.70	2.90
4/10/79	CPI-133	33.20	4.10	12.80	2.70
4/10/79	CPI-134	29.10	2.90	10.10	1.90
4/11/79	CPI-135	32.00	3.00	12.00	0.70
4/12/79	CPI-136	33.00	1.80	12.70	3.60
4/12/79	CPI-137	31.20	2.20	9.10	3.80
4/12/79	CPI-138	33.40	1.50	12.90	1.00
4/12/79	CPI-139	34.90	3.90	13.90	2.60
4/13/79	CPI-140	31.00	2.90	11.30	2.00
4/13/79	CPI-141	33.90	2.00	13.30	0.90
4/17/79	CPI-142	31.90	4.50	14.20	0.70
4/17/79	CPI-143	36.40	0.20	14.90	0.10
4/18/79	CPI-144	36.20	8.40	14.80	5.60
4/19/79	CPI-147	27.80	1.10	9.20	0.27
4/20/79	CPI-148	28.90	0.40	9.47	0.83
4/21/79	CPI-149	29.30	3.40	10.30	2.20
4/23/79	CPI-150	32.70	4.50	12.50	3.00
4/23/79	CPI-151	37.20	8.00	15.50	5.30
4/25/79	CPI-153	29.20	5.80	10.20	3.80
4/25/79	CPI-154	35.00	3.10	14.00	0.70
4/30/79	CPI-155	31.90	3.40	14.70	5.70
4/30/79	CPI-156	28.50	1.20	9.40	1.10

Historical Data

TABLE 16 (Continued)

Date (Day/ Month/ Year)	Test Number	Liquid Limit (LL)		Plasticity Index (PI)	
		X	R_2	X	R_2
5/1/79	CPI-157	29.70	1.50	10.50	1.00
5/1/79	CPI-158	28.20	0.30	9.50	0.20
5/1/79	CPI-159	28.30	0.80	9.70	0.50
5/2/79	CPI-160	29.30	3.60	10.20	1.40
5/2/79	CPI-161	32.90	3.20	12.60	2.20
5/2/79	CPI-162	36.10	1.90	14.80	1.20
5/2/79	CPI-163	38.00	10.10	16.00	6.70
5/3/79	CPI-164	27.90	5.10	9.30	5.70
5/8/79	CPI-165	33.00	0.10	15.00	2.30
5/9/79	CPI-166	33.10	4.90	12.70	3.30
5/10/79	CPI-167	38.00	11.30	16.00	3.70
5/15/79	CPI-168	28.70	0.20	12.30	2.50
5/16/79	CPI-169	28.90	6.90	9.80	3.30
5/17/79	CPI-170	35.80	2.20	13.10	2.90
5/18/79	CPI-171	38.00	2.70	16.00	1.80
5/22/79	CPI-172	35.30	2.30	14.20	0.80
5/24/79	CPI-173	33.00	5.00	15.00	1.00
5/29/79	CPI-174	38.00	11.60	16.00	3.70
5/30/79	CPI-175	28.40	0.50	12.30	2.50
5/31/79	CPI-176	28.90	2.60	9.80	0.40
6/1/79	CPI-177	31.50	1.20	10.20	2.30
6/5/79	CPI-178	32.70	1.30	12.50	0.10
6/6/79	CPI-179	31.40	0.90	12.60	2.00
6/6/79	CPI-180	30.50	4.40	10.60	3.40
6/6/79	CPI-181	34.90	6.30	14.00	4.20
6/6/79	CPI-182	28.60	3.20	9.80	0.60
6/7/79	CPI-183	31.80	0.20	10.40	1.30

Process Control Data

TABLE 16 (Continued)

Date (Day/ Month/ Year)	Test Number	Liquid Limit (LL)		Plasticity Index (PI)	
		X	R_2	X	R_2
6/8/79	CPI-194	31.60	1.60	11.70	0.10
6/12/79	CPI-195	33.20	0.90	11.60	0.39
6/13/79	CPI-196	32.30	0.90	11.21	1.61
6/14/79	CPI-197	33.20	3.10	12.80	2.00
6/14/79	CPI-198	30.10	1.50	10.80	0.90
6/14/79	CPI-199	31.60	2.00	11.70	0.60
6/15/79	CPI-200	29.60	2.20	11.[illegible]	2.40
6/15/79	CPI-201	31.80	1.60	13.50	3.06
6/19/79	CPI-202	30.20	11.70	10.[illegible]4	1.42
6/20/79	CPI-203	28.50	0.70	11.86	2.66
6/20/79	CPI-204	27.80	0.20	9.20	2.80
6/21/79	CPI-205	27.60	0.40	11.40	0.50
6/22/79	CPI-206	28.00	2.60	10.90	0.70
6/25/79	CPI-207	30.60	0.60	10.20	3.50
6/26/79	CPI-208	31.20	0.40	13.70	1.90
6/27/79	CPI-209	31.60	2.10	15.60	1.70
6/28/79	CPI-210	33.70	3.45	13.90	1.50
6/29/79	CPI-211	30.25		12.40	

Process Control Data

[a]Based on 24 subgroups of size n = 1 of historical data to establish control limits and 45 subgroups of size n = 1 of subsequent process control data.

Liquid Limit Calculations.

1. $\overline{X}' = \dfrac{\sum_{i=1}^{N} X_i}{N} = \dfrac{\sum_{i=1}^{24} X_i}{24} = \dfrac{780.2}{24} = 32.5 = \overline{X}_1$

2. $\overline{R}_2 = \dfrac{\sum_{i=1}^{m} R_2}{m} = \dfrac{\sum_{i=1}^{23} R_2}{23} = \dfrac{77.0}{23} = 3.3$

3. Tabulation of Individuals: $\overline{X}'$ and σ' unknown

   a. Target $= \overline{X}_1 = 32.5$

   b. UCL $= \overline{X}_1 + \dfrac{3\overline{R}_2}{d_2} = \overline{X}_1 + 2.66\,\overline{R}_2 = 32.5 + 2.66\,(3.3)$

   $= 41.3$

   c. LCL $= \overline{X}_1 - \dfrac{3\overline{R}_2}{d_2} = \overline{X}_1 - 2.66\,\overline{R}_2 = 32.5 - 2.66\,(3.3)$

   $= 23.7$

   Note: $d_2 = 1.128$ (from Table 1; $n = 2$)

4. Tabulation of Moving Range of Two Consecutive Observations: $\overline{X}'$ and σ' unknown

   a. Target $= \overline{R}_2 = 3.3$

   b. UCL $= D_4\overline{R}_2 = 3.27\,(3.3) = 10.8$

   c. LCL $= D_3\overline{R}_2 = 0$

   Note: $D_4 = 3.27$ (from Table 3; $n = 2$)

   $D_3 = 0$ (from Table 3; $n = 2$)

Plasticity Index Calculations.

1. $\overline{X}' = \dfrac{\sum_{i=1}^{N} X_i}{N} = \dfrac{\sum_{i=1}^{24} X_i}{24} = \dfrac{301.1}{24} = 12.5 = \overline{X}_1$

2. $\overline{R}_2 = \dfrac{\sum_{i=1}^{m} R_2}{m} = \dfrac{\sum_{i=1}^{23} R_2}{23} = \dfrac{53.9}{23} = 2.3$

3. <u>Tabulation of Individuals: $\bar{X}'$ and σ' unknown</u>

   a. Target $= \bar{X}_1 = 12.5$

   b. UCL $= \bar{X}_1 + \dfrac{3\bar{R}_2}{d_2} = \bar{X}_1 + 2.66\ \bar{R}_2 = 12.5 + 2.60\ (2.3)$

   $= 18.6$

   c. LCL $= \bar{X}_1 - \dfrac{3\bar{R}_2}{d_2} = \bar{X}_1 - 2.66\ \bar{R}_2 = 12.5 - 2.66\ (2.3)$

   $= 6.4$

   Note: $d_2 = 1.128$ (from Table 1; $n = 2$)

4. <u>Tabulation of Moving Range of Two Consecutive Observations: $\bar{X}'$ and σ' unknown</u>

   a. Target $= \bar{R}_2 = 2.3$

   b. UCL $\doteq D_4\bar{R}_2 = 3.27\ (2.3) = 7.5$

   c. LCL $= D_3\bar{R}_2 = 0$

   Note: $D_4 = 3.27$ (from Table 3; $n = 1$)

   $D_3 = 0$ (from Table 3; $n = 1$)

Table 16 illustrates the tabulation format that could be used to document the Atterberg limits data. Target values (center lines) and control limits are placed above each column. It should be noted from Table 16 that the tabulation is divided into a historical data section and a process control data section. For illustration purposes, the historical data covers the month of April 1979 which was the first month in the current construction season. The central tendency and the control limits were based on the historical data for 24 subgroups of size $n = 1$. As subgroups are added to the tabulation, e.g., test data for May and June 1979, they should be compared with the appropriate control limits for any signs of lack of control. Lack of control may be identified by points exceeding the control limits or by presence

of extreme runs, as discussed in Chapter 3. However, identifying extreme runs in tabular format is more difficult than in control chart format. The Table 16 tabulation indicates good control as all subgroups in the process data control section fall within the control limits. Based on this fact, it appears that the contractor might be justified in reevaluating his control limits by using a larger historical data set (perhaps tests 1 - 60) to see if the limit range decreases.

Summary

Two process control techniques were presented in this chapter. Examples were provided to illustrate how the most important control characteristics could be documented with the control chart technique. This technique involves the use of charts of individual observations, range charts, trend indicator charts, and Shewhart control charts. Tabulation techniques should be used for less important control characteristics where documentation, as well as control functions, is desired. Both techniques utilize statistical control limits for distinguishing between normally expected chance and assignable causes of variation in the process. Different target optimum moisture contents may increase the number of control charts and tabulations to an unreasonable number. This problem was not resolved in this thesis and may be a topic of future research.

CHAPTER 6

SUMMARY AND CONCLUSIONS

With the advent and proven applicability of statistically based performance specifications in the highway construction industry, the need for research to define an effective process control system for a contractor on dam embankment construction has surfaced. Statistical process control appears to be a powerful tool which may be used to assist in meeting the embankment specifications for the most critical section of the dam which is the impervious zone. Some contractors may be familiar with process control techniques that are used in the highway construction industry; therefore, they could probably easily adapt the techniques to dam construction. Since the majority probably do not have this familiarity, this research was performed with the objective of providing practical guidelines which could be used as a part of a process control system.

Summary

A procedure was presented in order to aid a contractor in the development of a process control system for compaction of dam embankments. This procedure involved the following suggested steps:

1. Assignment of responsibility for process control.
2. Review of the embankment specification.
3. Development of a sampling and testing plan.
4. Selection of documentation techniques.
5. Selection of a format for recording of data.

6. Selection and establishment of the control limits.

7. Selection of the interpretation criteria.

8. Investigation and elimination of assignable causes.

9. Evaluation of the system.

To illustrate its use, a process control system would have to be specifically designed for and applied on an actual project. Several trial runs may have to be made to produce a refined system. Due to the limited work accomplished on Dam A's impervious zone and the time constraints for this thesis, it was only possible to collect enough data to design a system. However, even if more data had been available, modifications would not have been feasible until the proposed process control method has been used on the actual project.

A U. S. Army Corps of Engineers Embankment Specification for Dam A was first reviewed to select existing specific process control activities for use in the system. The impervious zone was ultimately selected to be controlled using process control techniques.

Two major criteria used to establish the sampling and testing frequency of the process control system were: (1) length and costs involved in testing; and (2) subgroup size. Changes in soil testing methods may alter the frequency of testing as methods such as the nuclear densometer become accepted.

While it may be suggested that subgroups of size $n > 1$ be employed on all characteristics, it was felt to be impractical for the lengthy and costly soils testing procedures. Consequently, the example methods shown employed subgroups of size $n = 1$, with the exception of a field dry density example which employed subgroups of size $n = 2$. The illustration of subgroup size $n = 2$ was included because on a

construction project, if the proper system for taking tests is designed, a subgroup size $n = 2$ may not be unrealistic. The basic reason subgroup size $n = 2$ was not used to group and analyze data in this thesis is because the "historical data" used had not been corrected in a logical random fashion which allowed that approach to be used. If a contractor were setting up a system initially, he could take the tests in such a way (e.g., one test in the morning and one test in the afternoon) so that they could be logically grouped into subgroup size $n = 2$. The practical construction considerations of selecting such a subgroup size was not researched in this thesis. A random sampling plan was presented based on a planar area of one lift thickness with a 5,000 cubic yard minimum to randomly locate the test location in the Lot.

Documentation of the process control activities involves the use of control chart techniques for specific key characteristics and the use of tabulation techniques for the remaining characteristics of the impervious zone. Both techniques involve the determination of the central tendency and the process dispersion by means of statistical control limits. The control limits were established by using data obtained from the Corps district responsible for Dam A. Once the control limits had been calculated, they were compared with the data to classify assignable causes. The major attempt at identifying assignable causes would have to be made during the actual use of the process control system.

Observations: Dam A

It should be noted that the process control system developed in this thesis was not intended to represent the ideal system for every dam. The system was devised for a particular dam based on a particular embankment specification. Each dam would have its own peculiarities, including specification limits and compaction methods. The application of the proposed system to another dam would require a re-examination of the proposed activities.

It is the writer's belief that the proposed process control system will provide a much better basis for making decisions and isolating causes of problems in the process. While this system is not expected to overload the laboratory technician who is unfamiliar with the statistical techniques, a reduced sampling frequency may be desirable if the system does become too burdensome.

Complete and effective process control, in the writer's opinion, requires the use of a large number of control charts and tabulations. If the central tendency and dispersion of each control activity listed in the embankment specification were controlled, a contractor would need approximately 57* sets of charts or tabulations. Elimination of any of these activities would reduce the value of the total system. However, the system was reduced to 6* sets of charts or tabulations by concentrating on the impervious zone, since it is the most critical zone in the dam. It was felt that the other zones could continue to be controlled by existing control methods.

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*The number of control charts or tabulations is based on soil from the same borrow area at the same optimum moisture content. As noted earlier, the number of control charts or tabulations will increase as 3 × the number of borrow areas and/or 3 × the number of optimum moisture contents.

According to the Contractor Quality Control (CQC) section (Appendix B) of the specifications, testing and documentation is the responsibility of the contractor. From the Corps' legal viewpoint, this is appealing. However, the Corps reserves the right to stop the project if the contractor's testing and documentation techniques are not satisfactory.

Conclusions

Statistical process control is a powerful tool, enabling contractors and the U. S. Army Corps of Engineers to gain valuable insight into the operations and characteristics of the embankment compaction processes. Through the use of a statistical process control system, the contractor could: (1) predict his future performance; (2) receive advanced warning of problems in his process that could affect his acceptance results; and (3) identify and eliminate those problems before they do affect his acceptance results. It is the belief of the writer that statistical process control should become an important part of a contractor's quality control program.

Recommendations to be drawn from this research are:

1. There is a need for guidelines to develop a statistical process control system for embankment compaction of the impervious zone.
2. A random sampling plan for process control of a dam should be set up on a planar basis with a one lift thickness in order to select testing locations.
3. In order for the tolerances given in the specification to provide effective process control, corresponding

range tolerances should be supplied to control the process dispersion.

4. In order to attain the optimum process control system for a dam, actual implementation of the proposed system would be required. The need for revisions and/or modifications could then be determined.

5. The specified acceptance lot size should be used as the process control lot size.

6. Both control charts and tabulations should be used to document and analyze the compaction process for the impervious zone according to the following pattern:

   - Control charts
     - Moisture content
     - Relative density
     - Dry density
     - Percent compaction
     - Sieve analysis
       - Gradation - No. 4 sieve
       - - No. 200 sieve
   - Tabulations
     - Liquid limit
     - Plasticity index
     - Specific gravity

7. The existing Corps of Engineers specified practices for the compaction process should be used on all of the other embankment zones on the dam.

8. A concentrated (i.e., perhaps doubling the frequency of tests) sampling plan should be used in order to obtain the historical data needed to establish the process control tendency and control limits early in the construction season. This would allow the control chart technique to be used for a greater portion of the construction season.
9. In cases where the contractor initially uses the Corps of Engineers supplied mean and limits for the control chart, it is important that the contractor evaluate the pattern of test results that are plotted in order to determine if the externally applied limits adequately describe his own process. If they do not, then he should develop the central tendency and limits based on the actual data that has been collected for his process.
10. Whenever it is possible to economically justify the decision, subgroup sizes of n greater than 1 should be used. It should again be noted that a sample size of $n = 1$ was used in the examples in this thesis because of the data limitations which the writer experienced on the Dam A project.
11. With respect to moisture content, the number of control charts could be reduced by using either the difference or ratio of the actual moisture content and the laboratory targeted optimum moisture content whenever the soil in question exhibits a series of optimum moisture contents.

Future Research

The development of the statistical process control system illustrated in this thesis represents only the first stage involved in providing efficient, as well as effective, process control for a dam embankment. Later stages that will result in the optimum process control system require the kinds of information and clarification that can be provided by future research into the area. Therefore, the following areas related to process control should be considered for future research:

1. An investigation of the effects that a change in each of the following would have on the performance of the process control system:
   a. Subgroup size
   b. Method of subgrouping
   c. Sampling and testing frequency
2. An investigation of the possibility of eliminating unnecessary parameters from the process control requirements.
3. A comparison of the cost and effectiveness of various degrees of contractor process control as related to the expected adjustment in payment which the contractor might expect with each degree of control.
4. Implementation of the developmental technique for establishing control charts early in a project and then actually applying them throughout the construction of the embankment.

5. A determination of the feasibility of expanding the process control system to all of the dam embankment zones.
6. A comparative investigation of the implications of applying process control systems which utilizes: (1) the stated specification target values and control limits; and (2) target values and control limits which are established from historical data and later revised as additional process control data becomes available.
7. An investigation of the approach involving the reduction in the number of required control charts by plotting the difference of actual moisture content and targeted optimum moisture content or by plotting the ratio of actual moisture content to the targeted optimum moisture content.
8. An investigation of the construction implications related to the reduction in control limit range which occurs when subgroups of size $n = 2$ are used instead of subgroup size $n = 1$.
9. An investigation of the minimum number of historical control tests that are needed to realistically establish control limits so that later major revisions are not required.
10. An investigation of the process control sampling system to enable subgroup sizes of $n = 2$ to be economically used and the impact this would have on the differences

between the calculated upper and lower control limits and the specification control limits.

11. An investigation of the method of subgrouping data to account for different optimum moisture contents and to reduce the number of control charts or tabulations to a reasonable workable number.

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APPENDIX A

U. S. ARMY CORPS OF ENGINEERS EMBANKMENT SPECIFICATION (ABBREVIATED)

This appendix presents an abbreviated embankment specification that is presently being used on Dam A. Information not directly related to compaction of the dam has been deleted where noted. Information directly referred to in the main text is designated by a broken underline.

EMBANKMENT

2I-1. GENERAL: The work covered by this Section consists of furnishing all plant, labor, and equipment, and performing all operations in connection with preparing the dam embankment foundation and processing, placing, spreading and compacting all permanent fills and backfills for the dam . . . in accordance with the Drawings and these Specifications . . .

2I-2. DEFINITION: The term "dam embankment" as used in these Specifications is defined as the earth and rock fill portions of the dam structure. . . ."Backfill" as used in this section is defined as that excavation refill which cannot be placed around or adjacent to a structure until the structure is completed or until a specified time interval has elapsed after completion.

2I-3. GENERAL CONDITIONS.

2I-3.1. Lines and Grades. The embankment and backfill shall be constructed to the lines, grades, and cross sections indicated on the Drawings, unless otherwise directed by the Contracting Officer. The Government reserves the right to increase or decrease the foundation widths and embankment slopes or to make such other changes in the embankment or backfill sections as may be deemed necessary to produce a safe structure. . . .

2I-3.2. Conduct of the Work. The Contractor shall maintain and protect the embankment and backfill in a satisfactory condition at all times until final completion and acceptance of all work under the Contract. . . . The Contracting Officer will require samples from the borrow areas and processing

plants, and from materials in place in the embankment and backfill at frequent intervals and the Contractor shall furnish equipment and labor as required to obtain these samples at no additional cost to the Government in accordance with the Special Provisions. Any approved embankment or backfill material which is lost in transit or rendered unsuitable after being placed in the embankment or backfill and before final acceptance of the work shall be replaced by the Contractor in a satisfactory manner and no additional payment will be made therefor. The Contractor shall excavate and remove from the embankment or backfill any material which the Contracting Officer considers objectionable and shall also dispose of such material and refill the excavated area as directed, all at no costs to the Government. The Contractor may be required to remove, at his own expense, any embankment or backfill material placed outside of prescribed slope lines.

2I-3.3. Materials. Materials for embankment construction will be obtained from required excavation, from borrow areas or existing stockpiles designated on the contract drawings, or from other areas approved by the Contracting Officer, except the processed sand and gravel and processed gravel may be obtained from off site sources or by processing pervious materials from the required excavation or designated borrow areas. The Contracting Officer will determine the suitability of each source and determine deposition in the embankment. No suitable material will be spoiled without prior approval of the Contracting Officer. All roots, limbs, and wood splinters shall be removed from embankment materials. Materials containing sod or other organic or perishable material in a quantity considered deleterious by the Contracting Officer shall not be used in the embankment.

2I-3.4. Haul Roads and Ramps. Deleted as noted above.

2I-3.5. Stockpiling. When the excavation from the Rock Quarry area, pervious borrow source, required excavation, or screening to meet gradation requirements progresses at a faster rate than placement in the fill being accomplished, such excavated or processed materials shall be stockpiled at approved locations and in an approved manner until their use is authorized. . . .

2I-3.6. Stockpiles from Prior Contracts. Deleted as noted above.

2I-3.7. Rock Quarry Area. The rock quarry is the primary source of impervious core and rockfill materials. Suitable impervious materials may be stockpiled where and as approved by the Contracting Officer. . . . . It is the intent of these specifications that the quarry be used in a fashion

that will generate sufficient rock of the specified quality and size to satisfy embankment fill requirements for each construction season. . . .

2I-3.8. Processing Plants. Deleted as noted above.

2I-3.9. Stockpiling Sandstone for Select Rock Slope Protection. Deleted as noted above.

2I-4. MATERIALS.

2I-4.1. Impervious Fill. Impervious materials shall be obtained from excavation of existing stockpiles established under prior contracts, common excavation of the right abutment for the dam, outlet works, and rock quarry, or from required excavation. . . . Prior to excavation, the Contractor will make the necessary explorations to define more definitely the areas from which he will obtain the impervious fill materials and present the data obtained from this investigation to the Contracting Officer. The impervious fill material to be placed in the core of the dam shall not contain more than 45% rock fragments which are greater than the No. 4 sieve size and shall have a minimum of 35% fines passing a No. 200 sieve size with a minimum PI of 8, except that the impervious fill placed against the foundation rock shall have a minimum PI of 10. Uniform silts and sands will not be used as impervious fill. In a 15-foot-wide zone immediately adjacent to the downstream sand and gravel drain and in the impervious blanket for the closure dam, the impervious fill will meet the requirements for impervious fill set forth herein except that it will also contain at least 15% by weight of sand and 15% gravel size particles. All stones and rock fragments larger than 6 inches measured by greatest dimension shall be removed at the source prior to hauling to the fill. Soft organic soils, frozen materials or other soils deemed unsuitable by the Contracting Officer shall be wasted as directed.

2I-4.2. Unprocessed Random Rock. Deleted as noted above.

2I-4.3. OMIT

2I-4.4. Unprocessed Select Rock. Deleted as noted above.

2I-4.5. Processed Minus 3-Inch Rock. Deleted as noted above.

2I-4.6. Processed Minus 3-Inch Rock Transition. Deleted as noted above.

2I-4.7. Processed Plus 3-Inch Rock. Deleted as noted above.

2I-4.8. Processed Pervious Materials. Deleted as noted above.

2I-4.9. Crushed Aggregate Roadway Surfacing. Deleted as noted above.

2I-5. FOUNDATION PROTECTION AND PREPARATION.

2I-5.1. Core Contact Area. Deleted as noted above.

2I-5.2. Protection of Shales in Core Contact Area. Deleted as noted above.

2I-5.3. Approval of Embankment Foundation. No fill shall be placed on any part of the embankment foundation until such areas have been inspected and given final approval by the Contracting Officer. The Contractor shall be required to complete a final foundation cleanup. . . .

2I-6. PLACEMENT AND SPREADING.

2I-6.1. General. The gradation and distribution of materials throughout each zone of the dam shall be such that the embankment will be free from lenses, pockets, streaks, and layers of material differing substantially in texture or gradation from surrounding material of the same class. Successive loads of material shall be dumped at locations on the fill as directed or approved by the Contracting Officer. No fill shall be placed upon a frozen surface, nor shall snow, ice, or frozen earth be incorporated in the embankment. Placing operations will be such as to avoid mixing of materials from adjacent sections as much as practicable. Equipment traffic on any embankment zone shall be routed to distribute the compactive effort as much as practicable. Ruts formed in the surface of any layer of spread material will be filled before that material is compacted. If, in the opinion of the Contracting Officer, the compacted surface of any layer of material is too smooth to bond properly with the succeeding layer, the surface shall be loosened by scarifying or other approved methods before material for the succeeding layer is placed. During the placing and spreading process, the Contractor shall maintain at all times a force adequate to remove all roots, debris, and oversize stone from all embankment materials. Unless otherwise directed, the embankment shall be maintained at approximately the same level regardless of the number of types of materials being placed. At all times, the impervious zone and a minimum 30-foot width upstream and downstream shall be maintained at the same level except for the crown for drainage described herein. . . .

2I-6.2. Impervious Fill. Impervious fill shall be placed and spread in layers not more than 8 inches in uncompacted lift thickness and compacted with the specified tamping roller. The first four lifts of impervious fill placed against the core contact surface in the flood plain and on

rock benches on the abutments shall be placed on 12-inch uncompacted lift thicknesses and compacted with the specified 50-ton rubber-tired roller. . . . If lenses, pockets, or layers of materials differing substantially in texture or gradation from surrounding material occur in the spread material, the layer shall be mixed by harrowing or any other approved method to blend the materials. Immediately prior to placement of impervious fill at the beginning of any season, a minimum of 16 inches of impervious fill shall be removed from the impervious fill surface, reworked and replaced in 8-inch lifts and compacted as described herein. . . .

2I-6.3. Unprocessed Random Rock. Deleted as noted above.

2I-6.4. OMIT

2I-6.5. Unprocessed Select Rock. Deleted as noted above.

2I-6.6. Processed Minus 3-Inch Rock. Deleted as noted above.

2I-6.7. Processed Minus 3-Inch Rock Transition. Processed minus 3-inch rock transition material shall be placed and spread in layers of 4-inch compacted thickness. . . . The direction of placement, spreading, conditioning, and compaction of this zone shall be parallel to the axis of the dam.

2I-6.8. Processed Plus 3-Inch Rock. Deleted as noted above.

2I-6.9. Processed Gravel and Processed Sand and Gravel. These materials shall be placed in 12-inch lift thickness in the floodplain, and on the abutments spread in uncompacted layer thicknesses compatible with that zone of rockfill material next to which it is placed so that the drainage fill and rockfill may be raised together. Methods of placement shall be controlled to minimize segregation of particle sizes and contamination with other embankment materials. . . .

2I-6.10. Oversized Rock. Deleted as noted above.

2I-6.11. Crushed Aggregate Roadway Surfacing. Deleted as noted above.

2I-7. MOISTURE CONTROL.

2I-7.1. General. The materials in each layer of the fill shall contain the amount of moisture, within the limits specified below or as directed by the Contracting Officer, necessary to obtain the desired compaction as determined by the Contracting Officer. Material that is not within the specified limits after compaction shall be reworked, regardless of density.

2I-7.2. Impervious. The moisture content after compaction shall be as uniform as practicable throughout any one layer of impervious materials. The moisture content after compaction shall be within the limits of 2 percentage points above optimum and 2 percentage points below optimum moisture content as determined by procedures set forth in Appendix VI, U. S. Army, Corps of Engineers, Engineer Manual EM 1110-2-1906, 30 November 1970, "Laboratory Soils Testing." The more plastic impervious material to be placed at the core contact surfaces and compacted with a rubber-tired roller shall not compacted when the moisture content is below optimum or more than 2 percentage points above optimum. Material that is too wet shall be spread on the embankment and permitted to dry, assisted by discing or harrowing, if necessary, until the moisture content is reduced to an amount within the specified limits. When the material is too dry, the Contractor will be required to sprinkle each layer on the fill. Harrowing, or other approved methods, will be required to work the moisture into the material until a uniform distribution of moisture is obtained. Water applied on a layer of fill shall be accurately controlled in amount so that free water will not appear on the surface during or subsequent to rolling. Should too much water be added to any part of the embankment, so that the material is too wet to obtain the desired compaction, the rolling on that section of the embankment shall be delayed until the moisture content of the material is reduced to an amount within the specified limits. If it is impracticable to obtain the specified moisture content by wetting or drying the material on the fill, the Contractor may be required to prewet or dry back the material at the source of excavation.

If, in the opinion of the Contracting Officer, the top or contact surfaces of a partial fill section become too dry to permit suitable bond between these surfaces and the additional fill to be placed thereon, the Contractor shall loosen the dried materials by scarifying or discing to such depths as may be directed by the Contracting Officer, shall dampen the loosened material to an acceptable moisture content, and shall compact this layer in accordance with the applicable requirements of Paragraph 2I-8.2 to densities comparable to the underlying embankment.

If, in the opinion of the Contracting Officer, the top or contact surfaces of a partial fill section become too wet to permit suitable bond between these surfaces and the additional fill to be placed thereon, the wet material shall be scarified and permitted to dry, assisted by discing or harrowing, if necessary, to such depths as may be directed by the Contracting Officer. The material shall be dried to an acceptable moisture content and compacted in accordance with the applicable requirements of Paragraph 2I-8.2 to densities comparable to the underlying embankment.

2I-7.3. Unprocessed Random, Unprocessed Select and Processed Plus 3-Inch Rockfill. Moisture content shall be such that hauling, spreading, and compaction equipment can operate with normal procedure.

2I-7.4. Processed Minus 3-Inch Rock and Minus 3-Inch Rock Transition. The moisture content shall be as uniform as practicable throughout each layer before it is compacted and the material shall not be compacted when the moisture content is lower than 2 percentage points below optimum or higher than 2 percentage points above optimum as determined by Corps of Engineers, Manual EM 1110-2-1906 without replacement for material retained on the 3/4-inch screen. When the material is too dry, the Contractor shall make provisions for the addition of controlled amounts of water at the site of processing by screening so as to produce a material with the moisture content within the specified limits.

2I-7.5. Processed Pervious Material. The processed sand and gravel and processed gravel shall be wetted, as directed, to facilitate compaction. The amount of water added to the material shall approximate that required to produce substantial saturation when the material is in the compacted state. Water shall be applied by power spray, hose, or other approved equipment which will uniformly wet the material without erosion or ponding.

2I-7.6. Crushed Aggregate Roadway Surfacing. Deleted as noted above.

2I-7.7. Impervious Fill for Temporary Protection. Deleted as noted above.

2I-8. COMPACTION.

2I-8.1. Compaction Equipment. Deleted as noted above.

2I-8.2. Impervious Fill. After a layer of material has been dumped and spread, it shall be harrowed if required to break up and blend the fill materials, unless harrowing is performed to obtain uniform moisture distribution. Harrowing shall be performed with a heavy disk plow, or other approved harrow, to the full depth of the layer. If one pass of the harrow does not accomplish the breaking up and blending of the materials, additional passes of the harrow may be required, but in no case will more than three passes of the harrow on any one layer be required for this purpose. When the moisture content and the condition of the layer is satisfactory, the lift shall be compacted with not less than six coverages of an approved tamping roller loaded as directed by the Contracting Officer. . . . Compaction equipment shall be operated such that the strip being traversed by the roller shall overlap the rolled adjacent strip by not less than 3 feet.

21-8.3. Processed Minus 3-Inch Rockfill Transition. After this zone has been conditioned by the procedure outlined in Paragraph 2I-6.7 and the proper moisture content is obtained, each layer shall be formally compacted by not less than two complete coverages of the approved 50-ton rubber-tired roller.

2I-8.4. Unprocessed Random Rock and Processed Minus 3-Inch Rockfill. After each layer of random and minus 3-inch rockfill has been dumped and spread, and the moisture content is in accordance with provisions of Paragraphs 2I-7.3 and 2I-7.4, the layer shall be compacted by not less than four complete coverages of the approved 50-ton rubber-tired roller.

2I-8.5. Unprocessed Select and Processed Plus 3-Inch Rockfill. After each layer has been dumped and spread, and oversized rock removed or broken down, it shall be compacted by not less than four complete coverages of the approved 50-ton rubber-tired roller or four complete coverages by the tracks of the approved crawler tractor.

2I-8.6. Processed Gravel and Processed Sand and Gravel. After each layer of processed gravel or sand and gravel has been dumped and spread, and has the proper moisture content, the layer shall be compacted by not less than four complete coverages of the approved 50-ton rubber-tired roller. . . .

2I-8.7. Crushed Aggregate Roadway Surfacing. Deleted as noted above.

2I-8.8. Additional Rolling for Compaction. If, in the opinion of the Contracting Officer, the desired compaction of any portion of the embankment is not secured by the minimum number of coverages specified, additional complete coverages shall be made over the surface area of such designated portion until the desired compaction has been obtained.

2I-9. BACKFILL AND EMBANKMENT FOR OUTLET WORKS CONSTRUCTION. Deleted as noted above.

2I-10. POTOMAC RIVER DIVERSION - COFFERDAM. Deleted as noted above.

2I-11. CLOSURE DAM. Deleted as noted above.

2I-12. SELECT ROCK SLOPE PROTECTION. Deleted as noted above.

2I-13. UNPROCESSED RANDOM ROCK TRENCH BACKFILL. Deleted as noted above.

2I-14. RECLAMATION OF ROCK BORROW AREA. Deleted as noted above.

2I-15. REMOVAL OF IMPERVIOUS FILL, ROCK, AND SAND AND GRAVEL BEDDING PLACED FOR TEMPORARY PROTECTION. Deleted as noted above.

2I-16. MEASUREMENT AND PAYMENT. Deleted as noted above.

2I-17. QUALITY CONTROL.

2I-17.1. General. The contractor shall establish and maintain quality control to assure compliance with contract requirements and shall maintain records of his quality control for all construction operations required under this section. A copy of these records, as well as the records of the corrective action taken, shall be furnished to the Government as required in the "Quality Control" Section in the Special Provisions.

In addition, the Contractor shall submit a monthly summary report, on the forms provided in the Special Provisions, of all Quality Control testing performed on embankment materials for each month that embankment material is placed. This report shall be submitted to the Contracting Officer no later than the fifth day of the month following the month in which the testing was performed.

In compliance with the provisions of Paragraphs 2I-4 and 2I-7 herein, the Contractor shall be responsible for the gradation and moisture content of embankment materials to the extent indicated in the following paragraphs or as otherwise indicated in these specifications.

2I-17.2. Impervious. Materials to be used for impervious fill shall comply with the requirements of Sub-Paragraph 2I-4.1, as well as all other relative paragraphs.

Gradation tests shall be performed on all impervious material to insure that all material used as impervious fill meets the requirements of impervious fill as specified in Paragraph 2I-4.4. Assurances should also be made that the material is well graded. A minimum of one gradation test shall be performed for each 5,000 cubic yards of material to be placed in the embankment, unless otherwise directed by the Contracting Officer. Tests will be required more frequently when the test results indicate that the soil in a particular area is of questionable or variable quality. Each gradation sample shall be at least 5 pounds in weight. Test results shall be furnished to the Contracting Officer within 48 hours after sampling. Any soils not meeting the required gradation will not be accepted as suitable material for the impervious fill. Soils that are in stockpile established by the Contractor or in the embankment which do not meet the gradation requirements of the specifications shall be removed and disposed of by the Contractor at no additional cost to the Government. Test procedures shall be those given in Appendix V, EM 1110-2-1906, 30 November 1970, "Laboratory Soils Testing." It shall be the Contractor's responsibility to remove all stones or rock fragments

larger than 2/3 of the lift thickness at the source of borrow. All earth work operations performed at the borrow site shall be controlled and a record made of the same. Unless otherwise directed by the Contracting Officer, a minimum of one water content determination on at least a 4-pound sample of the minus 3/4 inch fraction of the material and one Atterberg limits test is to accompany each gradation test. Additional water content determination will be required at the borrow source to assure that all material placed in the embankment meets the moisture requirements of Subparagraph 2I-7.2. In addition to the water content determinations which are to accompany each gradation test, a minimum of one water content will be required on the in-place impervious fill material before compaction for every 5,000 cubic yards of impervious fill placed. Water content determinations shall be in accordance with procedures set forth in Appendix I, U. S. Army Corps of Engineers, EM 1110-2-1906, 30 November 1970, "Laboratory Soils Testing," or by approved field methods. Adjustment to the moisture content of the impervous fill shall be made in accordance with Subparagraph 2I-7.2. After compaction, the impervious material in the embankment shall be within 2 percentage points above or below optimum moisture content as determined by compaction test procedures given in Appendix VI, EM 1110-2-1906, 30 November 1970, "Laboratory Soils Testing," modified to utilize the 6-inch diameter mold, the 5.5 pound hammer with a 12-inch drop, and without replacement for the material retained on the 3/4-inch sieve. Material placed at the core contact surfaces shall have a moisture content between optimum and 2 percentage points above optimum. Compaction tests shall be run to determine moisture-density curves for all types of material intended for use in the impervious sections of the embankments. . . . A complete gradation, Atterberg limits and specific gravity determination will accompany each compaction test. . . . The Contractor shall establish horizontal and vertical controls in the borrow areas to the satisfaction of the Contracting Officer, and the location where each compaction test sample is taken shall be recorded and furnished to the Contracting Officer. Twelve-inch diameter sand cone density tests shall be performed at the minimum rate of one for each 5,000 cubic yards of impervious material placed. The density shall be determined by the sand cone density test procedure furnished by the Contracting Officer. . . . The Contractor shall furnish to the Contracting Officer the exact location of each field density test, which shall include the station, offset from axis of dam, and the elevation. Results of the tests shall be furnished to the Contracting Officer within 48 hours after sampling. . . .

2I-17.3. Unprocessed Rock Fill. Deleted as noted above.

2I-17.4. Processed Rock Fill. Deleted as noted above.

2I-17.4.1. Processed minus 3-inch rock and processed minus 3-inch rock transition. Deleted as noted above.

2I-17.4.2. Plus 3-inch rock. Deleted as noted above.

2I-17.5. Processed Gravel and Processed Sand and Gravel. Deleted as noted above.

2I-17.6. Crushed Aggregate Roadway Surfacing. Deleted as noted above.

2I-17.7. Random Backfill. Deleted as noted above.

2I-17.8. Pervious Backfill. Deleted as noted above.

2I-17.9. Gravel, Cobble, and Boulder Material. . . Deleted as noted above.

2I-17.10. Select Rock Slope Protection. Deleted as noted above.

2I-18. SUBMITTALS FOR GOVERNMENT APPROVAL. Submittals shall be in accordance with the contract clause entitled "Submittal Procedures" of the SPECIAL PROVISIONS. The Contractor shall submit to the Contracting Officer for approval shop drawings, material lists, etc., for items including but not limited to the following:

2I-18.1. Embankment.

(a) Proposed processing plant operation.

(b) Plan for stockpiling random earth material to be used for quarry reclamation.

(c) Plan for stockpiling select rock slope protection material.

(d) Monthly summary report of Quality Control Testing.

2I-19. OMIT

2I-20. "Sand and Gravel Bedding", . . . Deleted as noted above.

APPENDIX B

CONTRACTOR QUALITY CONTROL (CQC)

This appendix will present a Contractor Quality Control (CQC) section of the U. S. Army Corps of Engineers specifications currently being used on Dam A. Nonapplicable portions have been deleted where noted. Information directly referred to in the main text is designated by a broken underline.

CONTRACTOR QUALITY CONTROL (CQC)

1. GENERAL: The Contractor shall provide and maintain an effective quality control program that complies with the General Provision paragraph "Contractor Inspection System."

> The Contractor shall (i) maintain an adequate inspection system and perform such inspections as will insure that the work performed under the contract conforms to contract requirements, and (ii) maintain and make available to the Government adequate records of such inspections.

The burden of proof of contract compliance is placed on the Contractor and not assumed by the Government. The Contractor's quality control will not be accepted without question and the right to inspect or verify at any time is reserved by the Government.

2. PRE-CONSTRUCTION CONFERENCE: After the contract is awarded and before construction operations are started, the Contractor shall meet with the Contracting Officer, or his representative, and discuss quality control requirements. The meeting shall develop mutual understanding relative to details of the system, including the forms to be used for recording the quality control operations, inspections, administration of the quality control system, and the interrelationship of Contractor and Government inspection.

3. QUALITY CONTROL SYSTEM: The Contractor shall establish a quality control system to perform sufficient inspection and tests of all items of work, including that of subcontractors, to insure conformance to applicable specifications and drawings with respect to the materials, workmanship, construction, finish, functional performance,

and identification, with emphasis on the surveillance, tests and submittals required in the Technical Provisions of the contract specifications, including applicable in-plant inspection. This control will be established for all construction except where the Technical Provisions of the contract provide for specific Government control by inspections, tests or other means. The Government reserves the right to direct the location of tests required by the contract Technical Provisions. Any of the tests that, when performed, do not indicate compliance with the contract requirements will be reported to the Government immediately, and will not be considered as a test to satisfy the number of tests required by the contract. The Contractor shall notify the Contracting Officer or his authorized representative in writing of any proposed change to the Contractor's quality control system; no such change shall be implemented prior to acceptance in writing by the Contracting Officer or his authorized representative.

3.1 Review Submittals: . . . The Contractor's control system will be keyed to the proposed construction sequence in a manner to prevent construction deficiencies and/or delays caused by submittals lacking content or text required by the contract Technical Provisions. The Contractor will designate by name the quality control representative responsible for review, certification and submittals of shop drawings.

3.2 Quality Control Procedures: The Contractor's quality control system at the job site shall follow a three-step procedure consisting of (a) a Preparatory Inspection; (b) an Initial Inspection; and (c) Follow-up Inspections. The Contractor's quality control representative will advise the Government's site representative at least 24 hours prior to all preparatory and initial inspections. The preparatory and initial inspections will be attended by the applicable quality control representative and the Contractor's individual responsible for implementation of that portion of work at the site. Government personnel may participate in the preparatory, initial inspection and follow-up inspection.

3.2.1 Preparatory Inspection: Deleted as noted above.

3.2.2 Initial Inspection: Deleted as noted above.

3.2.3 Follow-Up Inspections: Deleted as noted above.

4. QUALITY CONTROL PLAN: . . . The Contractor will furnish the Contracting Officer within 15 days after receipt of notice to proceed, a quality control plan which will include the procedures, instructions, and reports to be used.

Unless specifically authorized by the Contracting Officer, no construction and/or off-site fabrication shall be started until the Contractor's entire quality control plan is accepted. . . . The Quality Control Plan will include as a minimum:

4.1 The quality control organization. This will be in the form of an organization chart that shows names and specific responsibilities of each of the quality control personnel.

4.2 The qualifications of each person performing inspection will be summarized giving education, licenses, present job position, and previous work experience.

4.3 A copy of a letter of direction to each of the Contractor's control representatives, outlining his duties, authority, and responsibilities, and signed by a responsible officer of the firm.

4.4 Methods of quality control including that for his subcontractor's work. (To include items to be inspected, types of inspection, duties of personnel, and methods the Contractor proposes to use to insure quality work.)

4.5 Test methods including, as specified, name of testing and inspection laboratories and names and qualifications of technicians employed by the Contractor to perform tests and inspections required by the contract. Laboratories shall be subject to approval of the Contracting Officer.

4.5.1 Latest calibration data for concrete testing machines . . . (where applicable) . . . . Calibration data for other testing equipment shall be made available for review upon request of the Contracting Officer.

4.5.2 A list of control tests which he understands he is to perform, not only by name, but also by numerical designation, together with a statement to the effect that the laboratory has a copy of each such procedure, and has facilities and serviceable testing equipment to perform tests conforming thereto. . . .

4.5.3 His understanding of the procedure to be followed, should his test results lack of compliance with contract requirements.

4.6 Procedures for reviewing. . . . Deleted as noted above.

4.7 Method of documenting quality control operation, inspection, and testing, including samples of proposed forms.

4.8 <u>Each copy of the complete plan</u> . . . Deleted as noted above.

5. QUALITY CONTROL LABORATORY: <u>The Contractor shall provide an on-site laboratory</u> staffed with qualified laboratory technicians and shall provide and maintain all measuring and testing devices, laboratory equipment, instruments, transportation, and supplies necessary to accomplish the required testing of soils . . ., and all other construction materials as specified under the appropriate provision of these specifications.

6. QUALITY CONTROL REPORTS: <u>The Contractor shall furnish a daily construction quality control report</u>. . . . The report shall include all inspections and tests made. It shall provide factual evidence that the required inspection or tests have been performed, including type and number of inspections or tests, the results, the nature of defects, cause for rejection and the corrective action taken. The daily report shall cover both conforming and defective items. . . . The report will be verified and signed by the prime Contractor's designated quality control representative. . . . Reports shall be submitted not later than the close of business on the first working day following the date of the report. . . .

6.1 <u>In addition to the daily Quality Control reports, the Contractor must submit monthly reports for Quality Control testing on the appropriate forms provided by the Contracting Officer</u>.

7. GOVERNMENT INSPECTION: The Government reserves the right to inspect at the source, supplies or services not manufactured or performed within the Contractor's facility. . . .

8. CONTRACTOR INSPECTION: The Contractor's inspection system shall provide for procedures which will assure that the latest applicable drawings, including shop drawings, specifications, and instructions required by the contract, as well as authorized changes thereto, are used for fabrication, inspection, and testing. . . .

9. WORK DEFICIENCIES: The Contractor will not build upon or conceal any work containing uncorrected defects. <u>If deficiencies indicate that the Contractor's quality control system is not adequate or does not produce the desired results, corrective actions in both the quality control system and the work will be taken by the Contractor. If the Contractor does not promptly make the necessary corrections, the Contracting Officer may issue an order stopping all or any part of the work until satisfactory corrective action has been taken</u>. . . .

10. QUALITY CONTROL PERSONNEL: The Contractor's quality control personnel shall be experienced and qualified in the speciality of work they are performing. . . .

a. One Construction Engineer . . . Deleted as noted above.

b. One soils Engineer . . . Deleted as noted above.

c. One Geologist . . . Deleted as noted above.

d. One Engineer or Geologist . . . Deleted as noted above.

e. One Concrete Technician . . . Deleted as noted above.

f. Two Experienced Lab Technicians . . . Deleted as noted above.

(Sample of typical contractor quality control report)

CONTRACTOR'S NAME
(Address)

DAILY CONSTRUCTION QUALITY CONTROL REPORT

Contract No. ______________________ Date ________________

Project Name ______________________ Report No. ___________

Weather ____

Phases of Construction in Progress (give briefly only phase of (sic) phases of work in progress)

Material and/or Equipment Delivered to Site (incl equipment demob)

Inspection Made (incl negative inspections, phase of work inspected and inspections)

Preparatory

Initial

Follow-Up

Tests Performed and Results of Tests (incl results of tests taken on on previous dates)

Verbal Instructions Received (list any instructions given by Government personnel on construction deficiencies, retesting required, etc., with action to be taken)

Changed Conditions/Delays/Conflicts Encountered

Remarks

SIGNATURE ______________________

Quality Control Inspector

Contractor's Verification: The above report is complete and correct and all material and equipment used and work performed during this reporting period are in compliance with the contract plans and specification except as noted above.

____

Contractor's Approved Authorized Representative

APPENDIX C

TEST DATA FOR IMPERVIOUS ZONE OF DAM A

This appendix contains the moisture and compaction data for the impervous zone that was used in Chapter 5 to illustrate the techniques of establishing control charts and tabulation methods. The data covers the period from April 1979 to June 1979, inclusive. The data will be presented in two parts: (1) results of Atterburg limit tests (Table 16, Chapter 5), and (2) results of compaction tests (Table 17). This breakdown is consistent with Table 10 which presents the characteristics to be controlled by both control charts and tabulation methods.

TABLE 17

RESULTS OF MOISTURE AND COMPACTION TESTS
FOR IMPERVIOUS ZONE MATERIAL

Date (Month/ Day/ Year)	Test Number[a,b]	Moisture Content (%)			Percent Compaction[c]	Field Dry Density[c] (lb/ft^3)
		Field	Optimum	Field - Optimum		
4/10/79	CPI-122	18.10	13.10	+5.00		
4/10/79	CPI-123	12.70	13.10	-0.40		
4/10/79	CPI-124	15.10	14.20	+1.90		
4/10/79	CPI-125	11.00	13.10	-2.10		
4/10/79	CPI-126	14.30	13.10	+1.20		
4/10/79	CPI-127	15.50	14.20	+1.30		
4/10/79	CPI-128	13.10	14.20	-1.10		
4/10/79	CPI-129	17.90	14.20	+3.70		
4/10/79	CPI-130	17.40	14.20	+3.20		
4/10/79	CPI-131	15.05	14.20	+0.85	104.69	116.14
4/10/79	CPI-132	14.59	14.20	+0.39	102.80	114.41
4/10/79	CPI-133	14.63	14.20	+0.43	101.80	118.86
4/10/79	CPI-134	15.20	14.20	+1.00	99.01	115.42
4/11/79	CPI-135	15.90	14.20	+1.70	100.96	112.19
4/12/79	CPI-136	16.04	14.20	+1.84	101.62	114.18
4/12/79	CPI-137	14.75	14.20	+0.55	102.90	117.70
4/12/79	CPI-138	14.70	14.20	+0.50	101.90	115.57
4/12/79	CPI-139	14.80	14.20	+0.60	102.89	116.75
4/13/79	CPI-140	15.10	14.20	+0.90	100.28	113.68
4/13/79	CPI-141	15.05	14.20	+1.05	102.23	115.97
4/17/79	CPI-142	14.50	14.20	+0.30		
4/17/79	CPI-143	15.50	14.20	+1.30	103.89	117.93
4/18/79	CPI-144	14.50	14.20	+0.30	103.76	117.77
4/18/79	CPI-145	14.60	14.20	+0.40		
4/18/79	CPI-146	14.80	14.20	+0.60	98.14	111.17

TABLE 17 (Continued)

Date (Month/ Day/ Year)	Test Number[a,b]	Moisture Content (%) Field	Optimum	Field - Optimum	Percent Compaction[c]	Field Dry Density[c] (lb/ft^3)
4/19/79	CPI-147	14.20	14.20	0.00	98.14	111.17
4/20/79	CPI-148	15.79	14.20	+1.58	99.17	112.38
4/21/79	CPI-149	15.10	14.20	+0.70	101.43	115.03
4/23/79	CPI-150	14.40	13.00	+1.40	104.48	118.98
4/23/79	CPI-151	14.60	13.00	+1.60	99.08	119.90
4/24/79	CPI-152	14.30	13.00	+1.30		
4/25/79	CPI-153	14.00	14.20	-0.20	102.00	116.86
4/25/79	CPI-154	14.10	14.20	-0.10	99.40	112.69
4/30/79	CPI-155	15.40	14.20	+1.20		
4/30/79	CPI-156	13.08	13.00	+0.08	100.51	117.28
5/1/79	CPI-157	17.30	14.40	+2.90	98.42	123.77
5/1/79	CPI-158	14.90	14.40	+0.50	98.62	111.73
5/1/79	CPI-159	16.00	14.40	+1.60	99.10	117.28
5/2/79	CPI-160	14.66	15.80	-1.14	101.60	112.32
5/2/79	CPI-161	14.54	15.80	-1.70	103.74	115.18
5/2/79	CPI-162	13.67	13.00	+0.67	98.20	117.75
5/2/79	CPI-163	15.75	15.80	-0.05	101.30	114.06
5/3/79	CPI-164	16.90	15.80	+1.10	101.69	111.23
5/8/79	CPI-165	14.06	15.40	-0.44	97.59	114.80
5/9/79	CPI-166	15.20	14.10	+1.10	98.62	115.96
5/10/79	CPI-167	15.03	15.80	-0.77	104.50	116.56
5/15/79	CPI-168	13.80	13.00	+0.80	97.40	115.72
5/16/79	CPI-169	13.63	14.40	-0.51	97.30	113.36
5/17/79	CPI-170	11.81	13.25	-1.41	99.80	118.20
5/18/79	CPI-171	12.37	13.25	-0.88	100.07	120.87
6/1/79	CPI-177	15.47	16.50	-1.03	100.67	114.36
6/5/79	CPI-178	16.13	14.40	+1.73	97.40	114.28
6/6/79	CPI-179	14.80	15.40	-0.60	99.30	112.83

TABLE 17 (Continued)

Date (Month/Day/Year)	Test Number[a,b]	Moisture Content (%) Field	Moisture Content (%) Optimum	Moisture Content (%) Field - Optimum	Percent Compaction[c]	Field Dry Density[c] (lb/ft^3)
6/6/79	CPI-180	16.34	16.50	-0.16	98.60	112/81
6/6/79	CPI-181	14.40	13.00	+1.10	98.90	120.35
6/6/79	CPI-182	14.80	13.00	+1.80	100.10	119.00
6/7/79	CPI-183	16.93	15.40	+1.53	98.40	111.90
6/8/79	CPI-194	18.85	18.00	+0.85	98.10	111.60
6/12/79	CPI-195	16.95	15.00	+1.95	99.60	119.10
6/13/79	CPI-196	14.10	14.60	-0.50	103.00	115.50
6/14/79	CPI-197	14.80	14.10	+0.70	101.60	116.80
6/14/79	CPI-198	14.70	14.10	+0.60	101.52	118.50
6/14/79	CPI-199	15.08	14.60	+0.48	100.88	116.44
6/15/79	CPI-200	14.85	15.50	-0.65	95.70	116.44
6/15/79	CPI-201	15.70	14.50	+1.20	103.16	115.10
6/19/79	CPI-202	14.50	16.20	-1.70	105.20	111.09
6/19/79	CPI-203	12.17	13.00	-0.93	98.70	119.23
6/20/79	CPI-204	15.80	14.20	+1.60	101.46	115.34
6/21/79	CPI-205	12.12	13.00	-0.88	102.10	118.38
6/22/79	CPI-206	12.98	13.00	-0.02	90.03	119.10
6/25/79	CPI-207	13.60	15.20	-1.60	103.40	115.10
6/26/79	CPI-208	13.10	13.00	+0.10	100.40	118.88
6/27/79	CPI-209	15.08	15.20	-0.12	97.66	113.05
6/28/79	CPI-210	15.76	15.40	+0.36	101.20	111.73
6/29/79	CPI-211	15.47	15.30	+0.17	98.26	114.10

[a] Test number is coded by embankment zone; CPI designates impervious zone.

[b] Test numbers CPI-172 to CPI-176 deleted (borrow source moisture tests only). Test numbers CPI-184 to CPI-193 deleted (trench material tests not applicable).

[c] Test numbers CPI-122 to CPI-130 and CPI-142, CPI-145, CPI-146, CPI-152, and CPI-155 were stockpile moisture tests for impervious zone material. Compaction and density tests were not applicable.

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ABSTRACT

This thesis provides a contractor involved in earthen dam construction with the appropriate tools and techniques needed to develop and implement a statistically based process control system for the impervious zone (or core). Initial research consisted of an extensive literature search to obtain background material related to compaction of embankments and obtaining the plans, specifications, and test data from the Corps of Engineers dam site used as an example in the thesis. Personal interviews were conducted with contractor and Corps personnel at the dam site directed toward gaining insight into the current practices involved in Corps dam construction projects and their comments concerning feasibility of a statistically based process control system. The practical situation observed and implemented on the Corps dam for embankment compaction of earthen dams was meshed with the theory of statistically based process control. A set of guidelines was developed for a contractor to use to set up a statistically based process control system for compaction of the impervious zone of earthen dams. The collected data were then used to demonstrate the statistically based process control techniques involved in analyzing test data for the impervious zone of an earthen dam.

Through the use of a statistical process control system, the contractor could predict his future performance, receive advanced warning of problems in his process that could affect his acceptance results, and identify and eliminate those problems before they do affect his acceptance results.